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Bulletin of the Museum of Comparative Zoölogy

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VOL. XLII.

GEOLOGICAL SERIES, Vol. VI. No. 1.

AN EXCURSION TO THE PLATEAU PROVINCE OF UTAH AND ARIZONA.

BY W. M. DAVIS.

WITH SEVEN PLATES.

CAMBRIDGE, MASS., U. S. A.:

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JUNE, 1903.

No. 1. — *An Excursion to the Plateau Province of Utah and Arizona.* By W. M. Davis.

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Introduction.

In the summer of 1902, the writer made his third visit to the region of the Colorado canyon. The results of the first visit in 1900 have already been published (a, b);[1] the results of the second visit in 1901 were of relatively small import and are here presented along with those of the third. The last excursion was undertaken partly as a means of providing opportunity in field work for some of our advanced students in geology at Harvard, two of whom, Messrs. Ellsworth Huntington and J. Walter

[1] Dates, letters, or page numbers in parenthesis refer to the bibliography at the close of the article.

Goldthwait, were enabled by the generous contributions from several friends of the geological department to spend five weeks in the plateaus north of the canyon. An abstract of their report has been published in the Journal of Geology and a fuller statement of their results will form a later member of this Bulletin.

Our itinerary, shown by a broken line with numbers for dates on Figure 1, was as follows: — From Provo by rail to Marysvale, July 12; Marysvale by wagon to Kanab, July 13 to 17; Kanab, in saddle with wagon outfit, to Mt. Trumbull and the Colorado canyon at Toroweap, July 18 to 21; on the esplanade of the canyon, July 22; from the canyon to Toquerville, July 23 to 29; about Toquerville with wagon, July 30 to August 5. On the latter date I left my companions at St. George to continue their study of the Toquerville district, and went by wagon and rail to Salt Lake City, and thence to Nevada and Oregon, as will be described in a later number of this Bulletin.

The observations made in 1900 led to certain departures from conclusions previously published, especially as to the time of the production of the great north-south faults by which the plateau province is traversed. It was believed that the greater part of the faulting had been accomplished before the uplift of the region by which the erosion of the Colorado canyon was initiated; that is, during the plateau cycle of erosion, so-called because the removal of a great thickness of rocks from the broad area of the plateaus north and south of the canyon was then effected (a, p. 119). It was further thought that during the canyon cycle of erosion extensive areas of weak Permian rocks were stripped from the uplifted region while the Colorado river was corroding its canyon (p. 139); and it was suspected that the western boundary of the uplifted region lay along the line of the Grand wash fault, on which a relatively late movement, long after an earlier movement, served to place the plateau region on the east above the Basin region on the west (p. 148).

The first of these conclusions will here be further substantiated; but at the same time it will be shown that modern faulting of large amount has taken place on the Hurricane fault fifty miles and more north of the canyon. Additional evidence will be presented as to the stripping of weak Permian strata from the plateaus north of the canyon during the canyon cycle. Perhaps the most important result of the summer's work bears on the recent movement along the Grand wash fault, which is now promoted from the rank of a supposition to that of a reasonable certainty, as will appear from the work of my student companions. Several collateral problems are discussed, as appears in the table of contents.

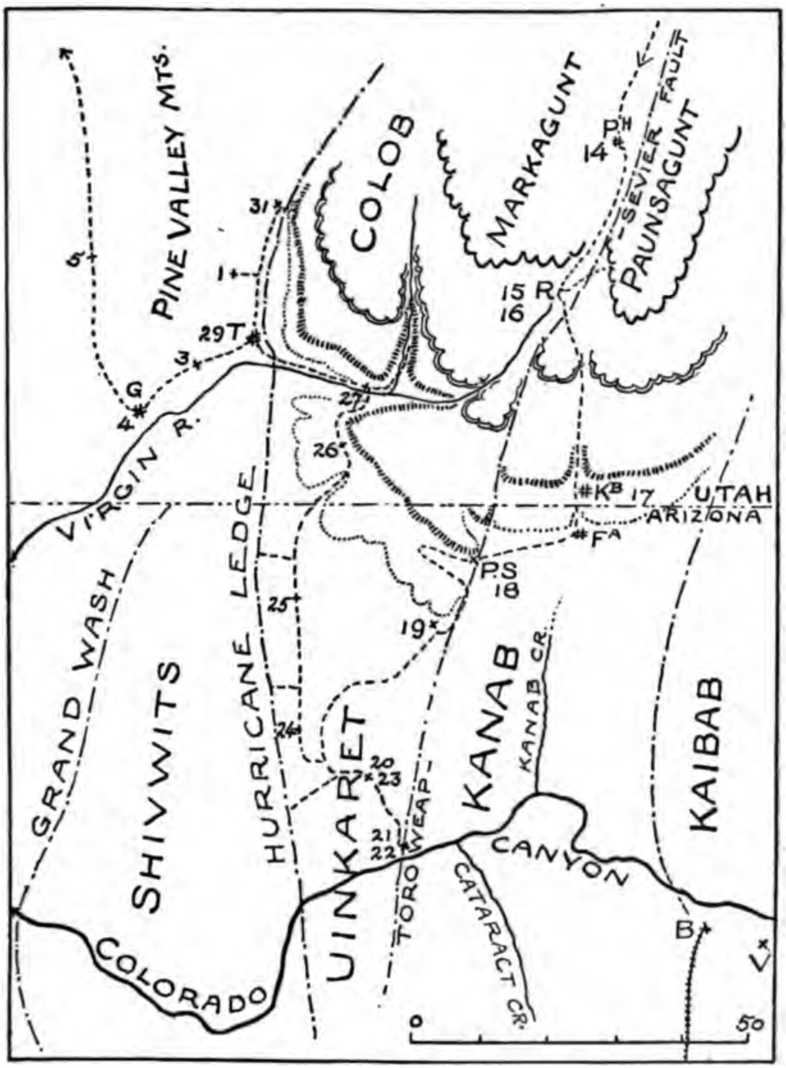

FIGURE 1.

Route map. The numbers alongside of the broken line showing the route followed indicate the dates in July (14–31) and August (1 to 5), 1902, when certain points were passed. The abbreviations are as follows: — A, Grand View Hotel; B, Bright Angel Hotel. These two points, south of the canyon, were visited in the summer of 1901. FA, Fredonia; G, St. George; KB, Kanab; PH, Panguitch; P. S., Pipe spring; R, Ranch; T, Toquerville.

The Sevier-Toroweap Fault.

Previous Statements. — The western part of the Plateau province is traversed by a series of monoclinal flexures and faults whose general course is from north to south as shown on sheet III of Dutton's Grand Canyon Atlas. Parts of two important faults are now to be described: the first is presented in this chapter under the double name given above; the second is the Hurricane fault, to which the next chapter is devoted. In Dutton's reports, the Sevier fault is traced southward from San Pete valley about two hundred and twenty miles to an ending near Pipe spring. Then after an unfaulted interval of twenty-five miles, the Toroweap fault is begun at a point about twenty miles north of the canyon, and continued closely in line with the prolongation of the Sevier fault to a doubtful termination twenty-five miles south of the canyon. These faults and their fellows are associated by Dutton with the Pliocene uplift of the region (see references in my previous article, b, p. 114), indeed, with so recent an epoch in the history of the plateaus that "every fault in the district is accompanied with a corresponding break in the topography." No instance is recalled by Dutton where "the lifted beds are planed off by erosion, so as to make a continuous level with the thrown beds" (b, p. 130). It has seemed to me, however, that this generalization is incorrect; that the faults are much older than the general (Pliocene) uplift of the region; that in several instances the existing escarpments are not the immediate product of faulting, but are the result of erosion on a faulted mass which may have been essentially baselevelled in the cycle of erosion initiated by the faulting, and which now shows escarpments along the fault lines because of differential denudation in a later cycle; and that the absence of an escarpment between the supposed ends of the Sevier and the Toroweap faults is therefore not sufficient evidence of the independence of these two great displacements.

It is certainly true, as will appear in the sequel, that relatively recent movement has taken place on some of the faults, so that the more resistant rocks still stand up in bluffs worn but little back from the fault line; an example of this kind will be described where the Toroweap fault crosses the canyon, and a much more imposing example is found in the northern part of the Hurricane fault. But there are often no signs of recent movement, and a large amount of erosion even in the stronger rock masses has usually been effected since their displacement occurred. The various lines of evidence that indicate a considerable antiquity for

the faults, and the possible continuity of faults across intervals where no break occurs in the topography have therefore an important bearing on the physical history of the region. The following account of certain significant localities on the line of the Sevier-Toroweap fault proceeds from north to south.

THE FAULT AT UPPER KANAB. — The district that includes the headwaters of the Sevier, the Virgin, and the Kanab, on the Kanab (Utah) Sheet, U. S. Geological Survey topographical maps, is of monoclinal structure with gentle eastward dip, in which the Sevier fault, Figure 2, uplifts the eastern half with a heave of nearly one thousand feet (Dutton, a, p. 31). The youngest of the dislocated strata are the Paunsagunt Tertiaries, which are classed as Eocene. Whether the fault occurred early or late in post-Eocene time can be best determined by inquiring into the changes effected by general erosion in the topography consequent upon faulting.

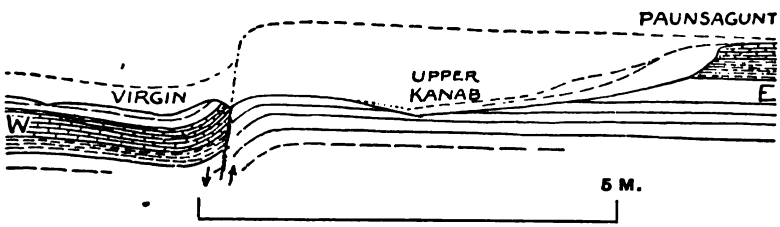

FIGURE 2.
General cross-section at Upper Kanab.

The most manifest effects of this fault upon local drainage would have been to produce longitudinal consequent streams in the trough parallel to and somewhat west of the fault line, and short consequent streams flowing west and eastward from the divide, as indicated by the dotted profile of Figure 2. The upper waters of the Sevier and of the Virgin may be in some way related to the inferred longitudinal consequent streams west of the fault, but the consequent divide east of the fault is now replaced by the subsequent valley of the Upper Kanab creek, eroded on the weak Cretaceous strata east of the fault and close along the line that should have initially stood at the greatest height. The simplest explanation for such a valley involves two cycles of erosion, separated by a regional uplift without significant renewal of faulting. During the first cycle it may be supposed that the cliff-making Paunsagunt strata were worn a few miles back (eastward) from the

fault escarpment, and that the weaker Cretaceous strata were thus exposed in a belt between the fault line and the retreating Paunsagunt cliffs; the drainage of the Cretaceous belt at this time being very probably effected by headward obsequent prolongations of the originally short west-flowing consequents, whereby the east-flowing consequents on the Paunsagunt had been progressively beheaded. In the second cycle, it is reasonable to infer that Kanab creek gained possession of the weak Cretaceous belt by headward erosion from the south, and that the east-flowing consequents on the Paunsagunt were thus still further undercut and beheaded.

There is some independent evidence of the correctness of these suppositions. Where the road from Panguitch to Kanab crosses the divide between the Virgin and Upper Kanab creek a little south of Ranch, there is a sheet of basalt that seems to spread horizontally across the

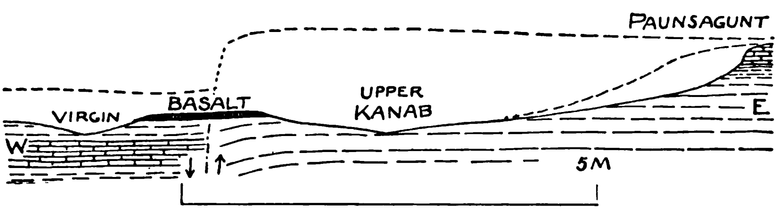

FIGURE 3.
General cross-section three miles south of Upper Kanab.

fault line, covering Tertiary and Cretaceous strata indifferently, as in Figure 3. It is thus suggested that at the time of the basalt eruption the effects of faulting had been locally obliterated, and this gives warrant for the first cycle of erosion. To-day the basalt forms an upland affording a fine view in nearly all directions, and the valleys are eroded several hundred feet beneath it; and this gives warrant for the second cycle of erosion. Moreover, the headwaters of Kanab creek are to-day extending their drainage area towards the north and east, and this suggests that they have been doing so in the past; in other words, Kanab is a growing subsequent stream, successfully invading the drainage area of its neighbors.

In view of so great a transformation from the topography supposedly initiated by the faulting to the existing topography produced by erosion, it seems necessary to give the Sevier fault a date somewhat earlier than late Tertiary time: yet it should not be thrown too far back toward the

Eocene, for the Eocene strata west of the fault seem to have been deformed by an east-dipping monoclinal flexure as in Figure 2, before they were faulted; and a significant period of post-Eocene time must be allotted not only to the production of the flexure, but also to the rearrangement of the deep-seated telluric forces, so that a fault with uplift on the east should succeed a flexure with uplift in the west.

The existing condition of the Sevier fault is well shown between Seaman's Ranch on the Virgin and the group of ranches known as the Upper Kanab on the creek of that name. The road forks between these two settlements and crosses the fault at points about a mile apart. The upper white and red members of the Tertiary series here exposed west of the fault are submaturely dissected, so that the eastern border of the Markagunt plateau in this district shows open valleys branching among rounded hills, whose slopes often exhibit contouring ledges. Three small shallow "lakes" or marshy meadows held back by fans from lateral ravines lie in the valley of the Virgin just west of the fault. The gentle eastward dip of the strata increases to about 10° near the lakes; but where the southern road crosses a white-soil ridge a little further eastward, the dip is 10° or more to the west. East of the ridge there is a rapid descent into the open valley of the Kanab (altitude, 6700′), eroded in the Cretaceous sandstones and shales and somewhat lower than the neighboring valley of the Virgin. The fault must pass close to the notch where the road crosses the ridge.

A mile north of another notch in which the northern road crosses the ridge of west-dipping Tertiaries, the Cretaceous strata rise in a hill adjoining the Tertiaries on the east, and here a ravine close along the fault line almost discloses the actual surface of faulting. The yellow-brown sandstones and gray shales of the Cretaceous dip 20° NW., while the white Tertiary limestones and shales dip about 10° W., but their bedding is not clearly shown. These dips, it will be observed, are locally reversed from the eastward slope of the presumably earlier monoclinal flexure and evidently result from the drag of the fault. The course of the fault line, measured by the trend of the ridge that follows it so closely, is here S. 25° W., true bearing. The valley of Kanab creek is broadly opened, and the general front of the Pink cliffs rises to the Paunsagunt plateau, attaining an altitude of nine thousand feet, about eight miles east of the fault line. The profile of the plateau is indented by the high-level valleys of east-flowing streams, whose heads are constantly undercut by the encroaching branches of the Kanab.

In view of these various facts, it seems inadmissible to regard the

Sevier fault as immediately responsible for the existing topography; the date of the fault must be sufficiently remote to allow much consequent and subsequent erosion after it occurred.

Our route southward from Upper Kanab led us obliquely to the east of the Sevier fault line, which was not seen again until we turned west from Fredonia toward Pipe spring. The two following sections are devoted to the notes made on the way there.

THE JURASSIC SANDSTONES. — The cross-bedding of the Jurassic sandstones exposed in the canyon of Kanab creek through the platform that fronts in the White cliffs, with an altitude of 6700 feet and a relief of a full thousand feet, was one of the most extraordinary structures seen during the summer. It has already been well described by Dutton (a, p. 150; b, p. 35), but no one can pass its superb escarpment without wishing to tell something of its wonders. Characteristic views of its form and stratification are given in Plates 1 A, 1 B, 2 A. The sandstone is white, clean, and even-textured, with its oblique layers slanting at angles of from 20° to 26°, and descending to great sweeping curves that turn gently tangent to the floor on which they rest. Southward dips are more common than northward. We looked in vain for the completed summit curves of the oblique beds: none were to be seen. Each group of oblique layers is truncated by the removal of its upper part, and the lower part that remains is too incomplete to indicate with certainty the origin of this very remarkable formation. Whatever was the entire original form of the successive deposits which the oblique layers possessed immediately at the time of their accumulation, the upper part of each group seems in all cases to have been more or less deeply worn away before the next higher group of layers was deposited. The surfaces of truncation are of gentle declivity and curvature, and often seem nearly or quite horizontal. Some of the groups of oblique layers are still twenty, thirty, or more feet in thickness, the successive layers descending with remarkable regularity and parallelism from top to bottom. Other groups are reduced to hardly more than a few feet in thickness, although their horizontal extent often exceeds a hundred feet, thus suggesting that their present vertical measure is but a small fraction of their original height. We saw no rippling; all the layers show very smooth lines on the outcrop face. The surfaces of truncation or local unconformity are marked by no uncertain deposits. The underlying layers are sharply cut off; the overlying layers rise gradually at first and then more steeply in long, sweeping curves. The sandstones seem to retain their cross-bedding up to the top of the cliffs, but in the upland north of the

escarpment they are overlaid by evenly bedded horizontal calcareous strata.

Wind action in an ancient desert seems more competent than any other agent to produce the observed structures, but we could not discover any critical and decisive proof of this suggestion. It would be difficult to select a more attractive problem in structural geology than would be offered to a student who should trace this extraordinary formation around its outcrops in the White cliffs until some demonstrable conclusion as to its origin should be reached. The dissection of the Jurassic platform back from the cliffs by obsequent, south-flowing streams gives abundant opportunity for viewing the curious structure of the sandstones. The little valley that our road followed southward gathers the drainage from a small area of open surface on the lower Cretaceous strata, gradually sinks below the Jurassic platform, and eventually joins the valley of Kanab creek near the ragged frontal escarpment. The cliffs, seemingly a good thousand feet in height, and the isolated dome-like outliers in front of them present long, smooth slopes of bare rock on which the lines of cross-bedding are beautifully and delicately engraved. The sandstone is so uniformly resistant that its slopes have no well-defined benches such as are usually developed in the weathering of horizontally stratified masses. Joints also have little influence here in guiding denudation. The cliffs have no ornamentation in the way of narrow clefts and slender pinnacles; their contours sweep in curves of large radius, and even the smallest of the outstanding buttes are of imposing size. The sandstone seems to disintegrate chiefly grain by grain, for there is usually little coarse talus at the base of the massive cliffs.

The canyon of Kanab creek through the Jurassic platform is followed by two basaltic flows that seem to proceed from a small cone a few miles to the north. The older flow, thirty or forty feet thick, forms a bench about eighty feet above the present valley floor where we saw it, and ends near the frontal escarpment. The younger flow forms the stream bed, where it is often buried in sand and gravel: it extends about a mile further south than the older one.

Kanab Canyon. — The Triassic platform, with an altitude of 6000 feet and a frontal relief of 1200 feet, is the southernmost of the great terraces by which the descent is made from the High plateaus to the broad upland in which the Colorado canyon is cut. Its frontal escarpment is known as the Vermilion cliffs, of which a characteristic view is given in Plate 2 B. The deep trench worn by Kanab creek through the Triassic platform is locally known as Kanab canyon, not to be con-

founded with the deeper canyon further south, where the same creek cuts down through the Kanab plateau to the Colorado river in the Grand canyon. The canyon in the Trias is of interest in giving an open section of nearly the whole Triassic formation, and in exhibiting the alternation of aggrading and degrading action by a stream in an arid region.

The Triassic strata are much more variable in texture than the Jurassic. They present many alternations from weak and thin-bedded muddy sandstones to thick, massive, resistant sandstones; and as a result the walls of this canyon are characterized by numerous benches. Cross-bedding is very common, though not on so remarkable a scale as in the Jurassic. The red color is very strong in many beds. It seems at first sight to prevail throughout, but a closer examination shows that some of the cliffs are made of a gray sandstone, whose outcrops are stained by the red wash from the overlying slope.

The uppermost of the red beds are seen in the base of the buttes that front the Jurassic escarpment; the Triassic platform is violently colored with them over large areas. The hue of the ground is so strong and so little concealed by the scanty vegetation that we saw passing cumulus clouds with a distinctly ruddy tinge on their under side, due to light reflected from the colored earth.

Kanab canyon has two terraces of well-stratified alluvium, usually of fine texture and containing lateral unconformities such as are to be expected in the deposits of aggrading streams; yet on the whole the stratification is remarkably even. The higher terrace is eighty or one hundred feet over the stream bed; it is less continuous than the lower one, which stands from forty to seventy-five feet over the stream. The channel below the lower terrace is the work of a series of floods beginning in the summer of 1883; a great part of the alluvium then accumulated along the valley was rapidly swept away. This seemed to be so excellent an example of the spasmodic action of floods in arid regions that I made special inquiry about it, and through the assistance of E. D. Woolley of Kanab secured an account written by his townsman, Herbert E. Riggs; the following is an abstract of the original: —

"At the time of the settlement of Kanab, in 1871, the creek ran at the level of the lower one of the two terraces that are now seen along its canyon. The meadow was about a quarter of a mile wide, with much swamp occupied with flags, bulrushes, rabbit brush and willows. This condition prevailed for about seven miles from the Trias escarpment (Vermilion cliffs) northward up the canyon to where the stream headed, and for about five miles southward,

where the meadow broadened as the creek divided and spread over the plain. It was almost impossible to ride a horse up the canyon on account of the mud-holes, quick sands and brushy thickets. The water in the creek was so low that from about May 20 to August 1, the stream would reach the village near the mouth of the canyon only from about day-break to 11 A.M.

In 1874, the meadow in the canyon was thrown open to stock, by which the vegetation was gradually destroyed. The creek was thus concentrated in fewer channels and its flow was increased more than half. Between 1874 and 1883, the canyon floor was fenced up, and the small fields were sowed with red-top and timothy; at the same time, the creek channel was better defined. A road was then constructed through the canyon.

The first great flood came on July 29, 1883. It swept away all of the farms and meadow lands in the canyon, as well as the field crops just south of the village, and scoured out a broad channel beneath the former valley floor. In passing Kanab, the flood was pronounced "as wide as the Missouri river," a rushing stream of liquid mud, bearing cedars, willows, and great lumps of earth. During the winters of 1884 and 1885, the plateaus of the Kanab headwaters received an unusually heavy snowfall; it lay in places ten feet deep on the level and lasted until April. Then as the sun thawed the snowbanks, floods occurred daily for three or four weeks and continued the deepening of the new channel through the canyon. As a result of three years' washing, the stream bed was cut down about sixty feet beneath its former level, with a breadth of some seventy feet, for a distance of fifteen miles."

The meaning of this remarkable change seems to be that canyons in an arid region are aggraded during periods of low water, and degraded at times of exceptional floods. It may be inferred that the duration of the aggrading periods is short in young canyons of relatively steep slope, and that only as the graded condition is approached and reached do longer and longer periods of aggradation come to alternate with spasms of degradation. If this inference is correct, it may be further inferred that the streams of arid climates differ in this respect chiefly in degree rather than in kind from streams in regions of more plentiful and regular rainfall: for the latter are known to clog their channels with bars and shoals at times of low water, and to scour them out during floods; but in the latter case the form of the channel after the flood closely resembles the condition before the flood, while it is greatly altered in the former case.

The scouring of Kanab canyon was checked at two or three points where the flooded stream happened to cut down its channel so near one side of the valley floor as to become superposed upon a previously buried rocky spur of the canyon wall. In such cases only a narrow and relatively shallow notch was cut in the rock, down-stream from which there

is now a waterfall; and the channel floor up-stream and down-stream from the fall is now at different levels.

A dam sixty-four feet high has been built across the entrenched stream bed about a mile north of the town of Kanab; an irrigating canal at about the level of the former valley floor is thus supplied with water for gardens and fields in and near the town. Since the erection of the dam, the depth of water in the pond above it has been much decreased by inwashed waste, thus illustrating one of the most serious difficulties — the rapid decrease of reservoir capacity — attendant upon the storage of water for irrigation in the arid region.

Close by the road from Kanab to Fredonia, at the point where it passes through a notch in the Shinarump escarpment, a step fault is seen in the gray Shinarump and the uppermost chocolate Permian beds, with a total uplift of not more than a few hundred feet on the east. The shattered parts of the escarpment has a breadth east and west, across the fault, of about a quarter of a mile, and six or more separate fractures occur within this distance. The apparently vertical slabs between the fractures appear to have been sheared so as to give their strata a dip of about thirty degrees to the west.

The Fault at Pipe Spring. — The outline map of the district around Pipe spring given in my previous paper (b, Fig. 7) may be here replaced by Figure 4, altered from its predecessor in several details, the most important of which concerns a branch fault with which the Pipe spring monocline is to be associated as a local feature; but full confirmation may now be given to my former conclusion that the Sevier fault continues its course at least ten or fifteen miles further south-southwest and that it is so old that the hard Triassic sandstones of the Vermilion cliffs in the eastern or uplifted (Kanab) plateau block have been worn back at least ten miles more than the same sandstones have retreated during postfaulting time in the western (Uinkaret) block. The latter point is of prime importance from its bearing on the date of the fault. At the time of faulting, it may be provisionally assumed that the Vermilion cliffs were essentially in line on the two sides of the line of fracture. The cliffs on the west of the line are retreating actively to-day and have undoubtedly retreated over a considerable distance since the faulting occurred; but the cliffs on the east of the line, uplifted with the eastern block and therefore more exposed to sapping by the underlying clays, have retreated so that they now stand ten miles north of the retreating western cliffs. This fact alone suffices to throw the date of faulting far back in the plateau cycle.

fine view of this district is obtained by an easy ascent of the sand-
monocline next northwest of Pipe spring, whence one may see the

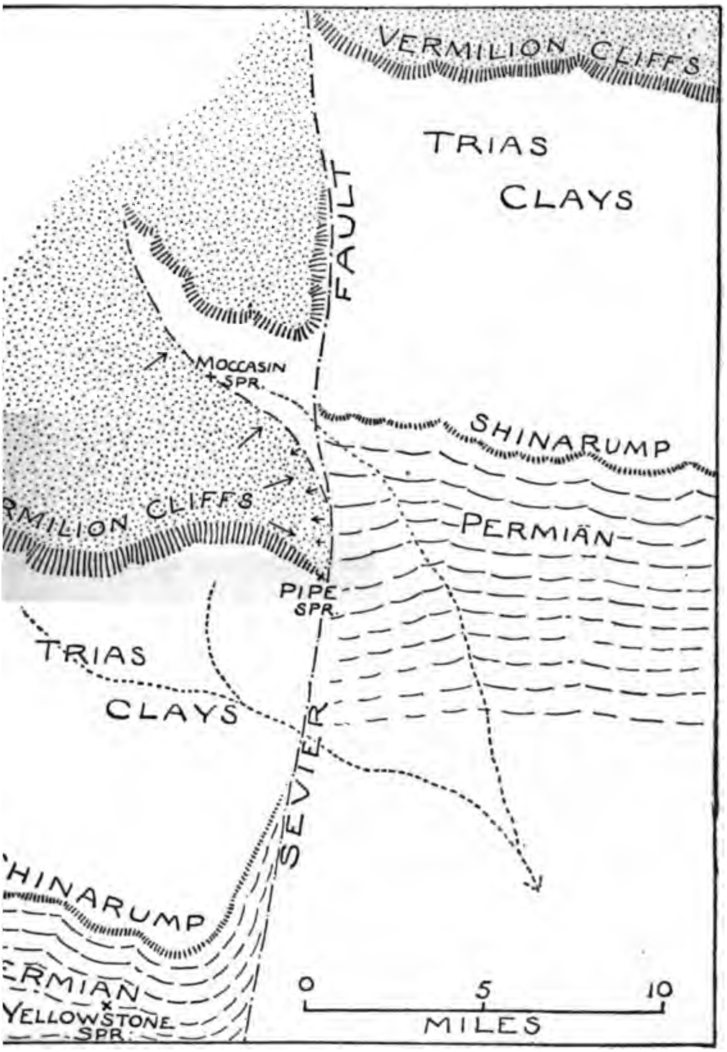

Figure 4.
Sketch map of the Pipe spring district.

sic and Shinarump escarpments terminating at the fault line in both
stern and the western plateau blocks. The general course of the

fault is here a few degrees east of north; its displacement must exceed one thousand or fifteen hundred feet. The bluffs of the great Triassic escarpment — the Vermilion cliffs — are seen coming westward in the eastern (Kanab) plateau block from a point far beyond Kanab: they end at the eastern side of Long valley, about ten miles north of our point of view. A broad and gently sloping graded platform leads forward from the base of the Triassic escarpment to the summit of the lower Shinarump escarpment, whose promontories are seen in profile far east of Fredonia. Although irregular in detail, the general course of this escarpment is held until the capping sandstones are abruptly cut off on reaching the fault line, about two miles away to the north: this is well illustrated in Plate 3 A. The Permian beds were well seen in late afternoon light, their lower and lower layers advancing in faint scarps and well-defined color bands five or more miles south of the Shinarump bluff, until the yellowish super-Aubrey beds appear about the head of lower Kanab canyon where Kanab creek cuts its way down in Kanab plateau, so as to join the Colorado at grade.

Turning now to the western (Uinkaret) block, the Triassic escarpment is seen to end eastward against the fault line at Pipe spring, where its margin with eastward dips lie next to the Permian clays of the eastern block. The Shinarump escarpment of the western block is seen to terminate eastward about ten miles south of Pipe spring, near Yellowstone spring. The relief of the escarpment there is much greater than that of its disconnected eastern fellow, because the graded surface of the plateau plain about Yellowstone spring lies much lower than it does further north, and a much greater thickness of Permian clays is therefore exposed in the strong frontal slope of the escarpment as one passes around its terminal bluff on the way to Yellowstone spring. As with the Triassic escarpment, so with the Shinarump: the retreat of its eastern member is some twelve miles in excess of that of its western member: and the latter must to-day be retreating with considerable rapidity, if one may judge by the fresh surface of the weak Permian clays under the capping sandstones. It is in these bluffs that one may see the slight unconformity of Shinarump on Permian noted by Dutton (b, p. 44, 80), and here illustrated in Figure 5.

THE MOCCASIN FAULT. — The eastern border of the Triassic upland back of Pipe spring is indented by a flat-floored, mile-wide valley heading to the northwest. The valley may be named after Moccasin spring on its western side. The strong Triassic sandstones are locally bent down so as to dip 10° or 20° northeastward as they descend toward the

valley on its southwestern side; and it is this local bending of the sandstones that produces the monoclinal flexure of Pipe spring. The sandstones on the further side of Moccasin valley are horizontal close to the main Sevier fault, except for the gentle northward dip that prevails through the whole region.

The floor of Moccasin valley — see Plate 3 A — is broadly covered with wash, but near its northeastern side the weak blue clays of the lower Trias are seen near the base of the enclosing escarpment. It is therefore concluded that the valley is underlaid by these weak beds, whose easy removal has caused the retreat of the Trias to the northeast. A branch fault must be here inferred, curving northwestward from the main fault along the southwestern side of Moccasin valley with a heave of twelve hundred feet or more on the northeast. The further end of the fault did not seem more than five or six miles away to the northwest, but it was not traced.

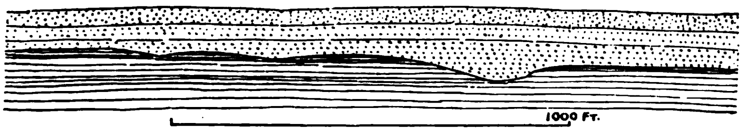

FIGURE 5.

Diagram of the unconformity at the base of the Shinarump.

Moccasin spring, like Pipe spring, supplies water enough for a small ranch. The two springs are about three miles apart; they are alike in flowing out at the eastern base of the sandstone monocline, where these permeable strata are faulted against impermeable clays; Triassic clays in the first case, Permian clays in the second.

EROSION IN THE PIPE SPRING DISTRICT. — The abundant erosion in the Pipe spring district since the production of the Sevier fault has had three characteristic but different effects, each controlled by the structure. First, all the outcrops of corresponding strata on the two sides of the fault are out of line by ten or twelve miles; this distance measuring the *excess* of escarpment-retreat in the uplifted eastern block over that in the western block, as has been pointed out. Second, where weak members of different horizons are brought together on opposite sides of the fault, the land surface is worn down to a relative lowland of even grade across the fault line; that is, the fault is there topographically extinguished. This is well shown just south of Pipe spring, where the lowland of the Triassic clays west of the fault line is drained to the low-

land of Permian clays east of the fault, the drainage flowing from the depressed to the elevated block. Third, where resistant members are faulted opposite to weak members, the resistant member forms an upland on one side of the fault overlooking the lower land eroded on the weak member on the other side of the fault; and this entirely independent of the heave and throw of the displacement. Thus the Triassic upland of the eastern block overlooks the lower land of Long valley, which I presume is eroded on the weak upper Trias; and the Shinarump of the eastern block overlooks, from a modest height to be sure, the lower land of the weak Triassic clays in Moccasin valley. In both these cases, the upland of resistant rocks is in the uplifted block. On the other hand, the Triassic upland of the western block overlooks lower lands of lower Triassic and Permian clays east of Pipe spring in the eastern block; and the strong Shinarump upland by Yellowstone spring overlooks the broad lower land of the lowest Permian layers in the eastern block. In both these cases, the effect of the fault is topographically reversed: the upland of resistant rocks is in the relatively depressed block; the relief is in spite of the fault and is evidently due entirely to erosion.

It follows from what has just been said that whatever arrangement of drainage may have been for a time consequent on the topography initiated by faulting, that arrangement is now replaced by a new one adjusted to the faulted structures. Stream beds and the general "wash" of the surface frequently cross the fault line, as often from the thrown to the heaved side as from the heaved to the thrown side. An example of this kind was described in my previous report (b, p. 128) from the neighborhood of Pipe spring, of special interest from the activity with which the "wash" that flows eastward across the fault from the thrown to the heaved side is undercutting and gaining area from the higher-lying westward wash. The divide between the two drainage areas is a low east-facing escarpment, known as Cedar ridge, now migrating westward and at a relatively rapid rate. It was seen only from a distance in 1900, but was visited in 1902. The varicolored lower Trias shales are here much better exposed than at any other point in the district. There can be no question that my previous interpretation of this divide was correct, and that the occurrence of such a divide draining towards and migrating away from the heaved block, is entirely inconsistent with a recent date for the fault at Pipe spring. There can therefore be no doubt that the Sevier fault hereabouts as well as at Upper Kanab is of considerable antiquity: it cannot be dated in the canyon cycle, but belongs rather early in the preceding plateau cycle.

The fifty miles of fault line between Upper Kanab and Pipe spring have not yet been closely described in any geological report or article. The effect of the fault and of subsequent erosion on the White cliffs of the Jurassic sandstones may be commended as offering excellent subjects for a thesis in structural geology in a region of great scenic attraction.

CONNECTION OF SEVIER AND TOROWEAP FAULTS. — It is on account of the second one of the above-mentioned effects of erosion that the southward extension of the Sevier fault to the Toroweap is not easily traced. South of the Shinarump escarpment by Yellowstone spring, the throw of the fault seems to decrease somewhat from its measure further north: for in Antelope valley (see sheet XXII, Dutton's Atlas) the middle Permian clays on the west seem to stand against the lower Permian clays and the yellowish super-Aubrey beds on the east. But in this district of weak strata there is little or no cause for the fault to express itself in the topography. It is probable, however, that a general view of the district, such as might bo obtained from the southermost Shinarump bluff, would disclose a dislocation of the color belts by which the gray and reddish clays and the yellowish calcareous beds are often revealed on the surface.

Still further south on the eastern side of Wonsits plain, a low bluff of super-Aubrey beds overlooks what I took to be Permian beds on the west, as mentioned in my previous essay: the fault probably passes near the base of this bluff, which lies near the final letter N of "Wonsits plain" on sheet VII of Dutton's Atlas. The geological coloring of this sheet gives a different interpretation from the one just suggested.

Still further south, about twenty miles beyond Yellowstone spring, the existence of the fault and a not-recent date for it are indicated by the attitude of the extensive lava beds that are there spread over the uplands on both sides of the inferred fault line. On the southeast, the lavas appear to lie for the most part with low edges on an upland of super-Aubrey or Aubrey limestone, in which relatively narrow valleys are opened where the lavas are absent. On the southwest, the lava beds, apparently at the same altitude as those on the southeast, form mesas with well-scarped edges that surmount slopes of lower Permian or super-Aubrey beds. The difference of horizon is not many hundred feet, but it seems to show that the lavas were spread out on a broad peneplain formed late in the plateau cycle by the far advanced erosion of the dislocated plateau blocks, as in Figure 6. To-day the peneplain is preserved only where it consists of resistant Aubrey beds, or where it is

covered with lavas. Where the peneplain was underlaid by weak Permian beds, its surface has now been worn away to a lower level in the Uinkaret block, and in the Kanab block also somewhat farther north. Truly, the fact that different horizons are here covered by the lavas might be interpreted as meaning that the western lavas were poured out before any fault had occurred and when the land surface was at a Permian horizon; that the eastern lavas were poured out after the land surface had there been worn down to an Aubrey horizon; and that a recent fault, passing between the two lava-covered areas, had raised the eastern lava field to the same level with the western. But this conclusion is extremely improbable because it is encumbered with the necessity of attributing to the lavas a highly specialized recognition of two areas that were afterwards to be divided by a fault, and of two different levels that were afterwards to be brought into accord by faulting.

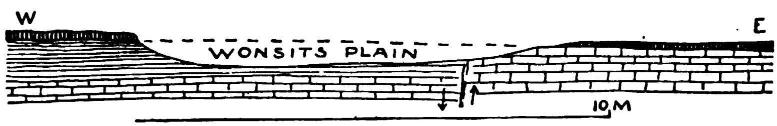

FIGURE 6.

Sketch section across Wonsits plain.

There is still a distance of some ten or fifteen miles from the lava beds to the more open part of Toroweap valley, through which the fault has not been traced. When this district is viewed from the top of Mt. Trumbull, there seems to be a west-facing bluff of Aubrey or super-Aubrey beds extending north from the east side of the valley past certain lavas in the valley head toward the low bluff of super-Aubrey beds, above-mentioned as overlooking Wonsits plain. This district is not easily examined in summer on account of the scarcity of springs. It might be studied earlier in the season when certain water pockets can be more safely depended upon, and I do not doubt that the fault might then be almost continuously traced into the Toroweap.

THE TOROWEAP FAULT AT THE GRAND CANYON. — As one descends into the broad Toroweap valley by the trail that leads down the slope of a grand lava cascade three miles southeast of Oak spring, it is easy to see that the eastern wall of the valley rises higher than the western, although both are rimmed with upper Aubrey limestone; and that the red lower Aubrey beds are abundantly exposed along the lower half of the eastern wall for fifteen or more miles north of the canyon, while

these beds make a much smaller part of the western wall. This evidence of a fault along the valley is abundantly confirmed at the canyon, where the dislocation in the southern wall is clearly seen in the grand view from Vulcan's throne, as Dutton has told (b, p. 93). In my excursion of 1900, our party had but a few hours at this point, and during much of that time I was so overcome with the heat that it was impossible for me to make any critical observations. During the past summer, much better opportunity for studying this most interesting locality was gained by camping over two nights, from July 21 to 23, on the esplanade just east of the fault line; the only drawback on this occasion being that our stay there was during a period of haze brought by the southwest winds, and accompanied by sultry nights as well as excessively hot days. We carried water for our own needs from Oak spring, and watered our horses at a muddy reservoir made by the stockmen just north of Vulcan's throne.

The point on which I previously felt constrained to differ from the conclusions presented in Dutton's report concerned the date of the Toroweap fault relative to the erosion of the canyon. It still seems necessary to regard the fault as for the most part of earlier origin than the canyon, because the valleys that follow the line of dislocation both north and south of the canyon are widely opened. Had the fault been produced after the erosion of the esplanade, that is, at so recent a date that even the vigorous Colorado has since then had time to carve only a narrow canyon, it would have been quite impossible for weak and intermittent wet-weather streams to have, in the same brief period, carved broadly open valleys, two or three miles wide, along the fault line. So late a date for the fault therefore makes it necessary to suppose that the broad north and south Toroweap valleys had been eroded during an earlier period, identical with that in which the esplanade was developed, and that the Toroweap fault line subsequently followed the course of the valleys: an extremely unlikely occurrence. It is much more probable that the greater movement of the fault antedated the erosion of the north and south Toroweap valleys, and that their location was in some way dependent on the fault.

On the other hand, a relatively recent additional movement of a hundred or more feet is clearly indicated by the dislocation of a lava bed in the floor of the south Toroweap valley close to the canyon rim, as described by Dutton (b, p. 94). A corresponding movement is indicated on the north of the canyon in the gulch between the eastern base of Vulcan's throne and the west-facing scarp of the esplanade, as in Figure 7. Near the base of the esplanade scarp there is a bench of firm black lava, which

has no fellow on the west side of the gulch where the slope consists wholly of tuff. Some of the tuff stands up in little ridges bordering the base of the ash cone and seems to have a steep dip to the west. The vertical displacement here indicated by the lava bed may be one hundred feet or more. A northward continuation of this subrecent movement is suggested by a low west-facing lava scarp that may be traced for a mile or more north of Vulcan's throne on the eastern side of Toroweap valley floor. A still more recent movement is indicated by a small but distinct scarp, about twenty feet in height, that traverses a gravel wash on the east side of the south Toroweap valley, somewhat east of the main fault line. This scarp was seen in a sunset view from Vulcan's throne, when in spite of its distance of about three miles, the low western sunshine

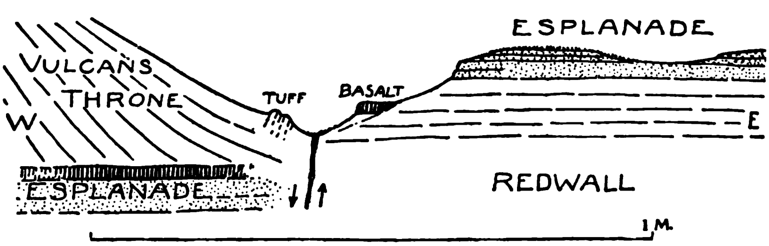

FIGURE 7.
Sketch section at Vulcan's Throne.

brought it distinctly to sight. A significant amount of faulting must therefore be recognized as having occurred near the canyon at least, after the esplanade had been formed and after lavas had been poured on its floor. On the other hand, there seems to be no sufficient reason for regarding the chief movement on the Toroweap fault, amounting to six hundred or seven hundred feet according to Dutton, as having occurred in the canyon cycle. Analogy with the neighboring great faults would suggest an earlier origin in the plateau cycle; this opinion is not at all contradicted by the dislocation of the esplanade, and it is supported by the considerable width attained by the Toroweap valleys, north and south of the canyon, as explained in my earlier article (b, p. 143, 184).

The decrease of the displacement northward along the valley reported by Dutton (b, p. 93) is probably more apparent than real; the heavy lava flows on the valley floor would tend to conceal the escarpments by which the fault is so clearly revealed at the canyon.

Camping on the Esplanade.

GENERAL FEATURES OF THE ESPLANADE. — The experience of camping in the esplanade was mentally impressive rather than physically enjoyable. The noon hours were oppressively hot, and even the nights were too sultry for refreshing sleep, but the latter discomfort was probably only a temporary element associated with the haze brought by the enervating southwest wind. The scenery is marvellous. The views from the salient corner of the esplanade next to the fault, and from the ash cone, Vulcan's throne, well repaid the discomfort that they cost.

The floor of the esplanade is rather even when taken all together, but it possesses a considerable relief in detail. It consists in about equal parts of clean-swept, cross-bedded, red sandstone — the "esplanade sandstone," or uppermost member of the red-wall group — and of stony, dusty waste in which an interesting desert flora finds root. Small rock basins or water-pockets are plentiful: many of them contained an inch or so of lukewarm, unsavory water at the time of our visit. A light thunder-shower — one of many that started down from the clouds — reached the esplanade at noon, July 22, making the bare rocks glisten for some distance up the canyon; but there was "not enough water to run," as the local phrase has it. Distances are not easily estimated because the dimensions of the enclosing cliffs are so much greater than those of the hills that one is accustomed to in regions of moderate relief. A point that at first sight seems within reach of an easy stroll demands a long walk before it is reached. The terrace of bright red sandstone — the "basal Aubrey sandstone" overlying the "esplanade sandstone" — that skirts the eighteen hundred foot Aubrey cliffs as a small detail of their imposing slope grows to a high bench when one comes to climb it.

The general floor of the esplanade declines gently to the rim of the inner canyon; one must walk along the very edge of the great bench to see down to the river, nearly three thousand feet below. Truly this enormous gorge is only half as deep as the whole canyon in the Kaibab; but there the eye wanders bewildered over the superabundant elaboration of gigantic lateral spurs and ravines, while here the impressive simplicity of form, as shown in Plate 4 A, lends great dignity to the prospect. It is certainly an unforgettable experience to stroll at leisure along the rim of the canyon, now looking across the esplanade to the great cliffs that rise to the plateaus, now looking down to the tawny

river, all in the glare of burning sunshine except for the deep shadows on the south wall of the canyon.

At certain points one may see the river for the better part of a mile, but the bends in its course soon carry it out of sight. Its most notable features are: — an apparently graded flow, the absence of flood-plain strips, foam-like patches of whitish sand along the water's edge, a slope of talus for several hundred feet over the river banks, and the projection of a delta fan more than half across the channel from the first large lateral ravine in the northern esplanade east of the fault line. This ravine joins the canyon at grade, although its drainage area from an amphitheatre in the Aubrey cliffs over the esplanade is not a tenth, perhaps not a twentieth of the Toroweap area. The slope of the southern wall of the canyon, measured on a photograph, is close to 60° : about a quarter of the wall consists of steeply graded, talus-covered slopes at an angle of 35° ; the remainder is made up of rock-faced cliffs, with slopes of 70° or more. There are five chief cliff belts, the strongest of which is on the upper red-wall limestone with a nearly vertical height of six hundred feet.

The salient corner, where the northern esplanade is cut off by the Toroweap fault, affords a superb view of the effects of this dislocation. The floor of the southern esplanade is foreshortened in the view from a point at its own height; it is in places bare, in places dotted over with cedars like a thinly planted orchard as in Plate 4 B. The extension of the esplanade west of the fault on the north side of the inner canyon is here concealed by Vulcan's throne; but it is well shown on the south side of the canyon two hundred or three hundred feet (according to the topographic map of the district) below its counterpart east of the fault. The descent from one level to the other is made partly by an abrupt scarp of the esplanade sandstone, and partly by a slope of the weaker beds that lie between the esplanade sandstone and the red-wall limestone. Directly at the base of the slope lies the sheet of lava by which the floor of south Toroweap valley has been held up; the lava west of the fault being just about at the level of the cliff of red-wall limestone (under the esplanade sandstone) east of the fault, as is clearly shown in Plate 5 A. It was an immense satisfaction to see all this from so suggestive a point of view as the corner of the northern esplanade. There I spent two memorable morning hours, taking refuge beneath overhanging ledges under the corner when the sunshine became unpleasantly strong, and then slowly retreating to a larger rock shelter near our camp, a mile back, for the hot hours of noonday.

THE VIEW FROM VULCAN'S THRONE. — The ascent of Vulcan's throne in the late afternoon afforded a much more comprehensive view than that of the morning. The ash cone to which a classic name has been — somewhat unfortunately — attached is marked on Dutton's topographic map (b, Atlas sheet VIII.) as having an absolute altitude of 5100 feet: it is therefore about six hundred feet higher than the lavas on the esplanade west of the fault in the Uinkaret block, six hundred feet higher than the esplanade next east of the fault in the Kanab block, and 3500 feet above the river whose channel lies a mile south of its summit; but it is 1200 feet below the upland of the Kanab plateau block on the northeast. When looking up the canyon from the cone, one has the view that has become famous in Holmes's wonderfully effective drawing (Dutton, b, Atlas sheet VI.); the esplanade stretching far eastward, enclosed by great cliffs and spurs of Aubrey, north and south, and trenched along its middle by the inner canyon. Holmes's graphic interpretation of the esplanade floor gives the impression of a greater number of evenly graded and waste-covered hills or mounds than I noted in the actual view, where the proportion of bare rock is unusually large: the softest forms are near the faulted edge of the northern esplanade, where a moderate amount of lapilli from Vulcan's throne cloak the surface.

The northward view shows the broad floor of the Toroweap valley, enclosed by promontories of normal Aubrey cliffs along the margin of the Kanab plateau on the east, and by Aubrey cliffs cloaked with a marvellous series of lava cascades from the Uinkaret plateau on the west; all this being portrayed with great fidelity in another of Holmes's drawings (Dutton, b, Atlas sheet V., lower view). This valley is, like its southern counterpart, exceptional in following a fault, the other drainage lines of the region being as a rule indifferent to faults. It is however very possible that, at the time when the faults occurred in the plateau cycle, drainage lines were instituted consequent upon the slopes of the dislocated surface of that time, and that some of the lines followed the depression along the junction of each pair of plateau blocks, as has been suggested in the account of the Sevier fault at Upper Kanab. In most cases these stream lines were broken up as the adjustment of streams to structures took place, as in the Pipe spring and Upper Kanab districts; but in the Toroweap district, where the postfault erosion was probably concerned for the most part with Permian and lower Trias clays (the Shinarump being the only resistant member of this part of the series),

the stream consequent on the faulting seems never to have been tempted from its original course.

The high floor of the Toroweap must certainly be referred to the floods of lava that have been poured into it, as was suggested in my previous essay (b, p. 189) and not to weakening of stream action due to change of climate. The deep incision of several neighboring lateral canyons of no larger or even of smaller drainage area than the Toroweap, but unobstructed with lava, leaves no room for doubt on this point. The same explanation must apply to the high floor of the South Toroweap valley, for although the lava there is of relatively small area, it is precisely in the right situation — at the mouth of the valley — to be most effective in retarding erosion. It is the breadth of the two Toroweap valleys that at first seems abnormal; but I am convinced that the difficulty here is more apparent than real. The breadth of these valleys, like that of the esplanade, is practically independent of the depth to which erosion has proceeded beneath the esplanade sandstone. The esplanade level once being reached by the valley stream, the widening of the valley goes on rapidly because the weak lower Aubrey beds waste easily and sap the upper Aubrey cliff at the top of the valley walls. The upper walls of the main canyon would not be less widely separated than they are to-day if during the actual lapse of time in the canyon cycle, the river had never cut the inner canyon below the esplanade: the Toroweap valleys would be hardly wider than they are even if their streams had cut down to grade with the main river, without hindrance from lava floods; good warrant for the latter inference being found in the rough equality of width between the upper Aubrey cliffs in the deep Cataract canyon (a southern branch of the Colorado) and in the shallow Toroweap (see Dutton, b, Atlas sheet VIII.).

It may be noted in passing that at a distant future stage of erosion, the existing re-entrants in the Aubrey cliffs on the west side of the Toroweap, down which the great lava flows have cascaded from the cones on the Uinkaret, will be converted into salients; for the Aubrey buttresses between the lava cascades will pretty surely weather back faster than the cascades themselves, inasmuch as the cascading lavas cover the weak lower Aubrey beds on whose weathering the retreat of the strong upper Aubrey so largely depends. In that distant future time, this district may therefore be expected to present, in horizontal plan, an exemple of inverted relief, — cliff re-entrants changed to cliff salients, — with which we are so familiar in vertical profile where ancient lava-flooded valleys have been transformed into existing lava-capped table mountains.

The view of south Toroweap valley from Vulcan's throne is more extensive than that from the corner of the esplanade (Plate 5 A). It is partially shown in one of Holmes's drawings (Dutton, b, Plate XVIII.). The further end of the valley turns gradually from south to southwest. The lower western wall curves out of sight and the higher eastern wall bends round so as to close the view; hence the fault must turn westward with the valley. The lavas of the south Toroweap were poured out before the inner canyon had attained nearly its present depth, yet not until the valley had been eroded several hundred feet beneath the esplanade sandstone; for the lava rests on a considerable thickness of ash (not distinctly shown in Holmes's drawing referred to above) exposed in the southern wall of the canyon, and yet the lava surface is at the west-esplanade level. The outburst of the lavas must have been long after the first and greater movement of the Toroweap fault, but the lava sheet is now broken by the recent smaller movement, apparently on or close to the old surface of fracture, as has already been stated. A short lateral gulch of the main canyon, apparently gnawed back along the new fault, divides the nearer part of the lava sheet into an eastern (higher) and a western (lower) portion. A small ash cone surmounts the latter; it has been partly undermined by the widening of the gulch. The dikes that rise in the wall of the canyon, as if to feed this cone, figured in Dutton's monograph (b, p. 96), confirm the date above suggested for these local eruptions with respect to the erosion of the inner canyon; most of the depth of the canyon must have been eroded after the dikes were intruded. Two other ash cones are seen further south: one is about a mile from the canyon, close to the scarp by which the dislocation of the esplanade can be traced far along the valley; the other is a mile or more beyond, on the lower Aubrey slope on the east side of the valley. Two small cones stand on the south esplanade, about a mile and a half east of the fault line. They are seen in Plate 4 B. They seem to be due to eruptions after the erosion of the canyon had nearly reached its present stage, for their lava flows into the head of a neighboring ravine whose length could not have been gained until the canyon was deeply incised. It seems remarkable that the ascent of lava to these cones should have so completely disregarded the opportunity of finding a vent in the canyon wall. There is no record that the south Toroweap has been visited by a geologist: all that is known of its structure depends on observations from the north side of the canyon, at distances of several miles. The southern end of the fault which guides the valley has not been closely determined.

The view westward down the canyon, Plate 5 B (see also Dutton, b, Atlas sheet V. upper view) is very unlike the eastward view. The normal esplanade of the southern Uinkaret, enclosed by Aubrey cliffs, is seen south of the canyon; it is cleft by a ravine that is fed with wet-weather wash from an Aubrey amphitheatre of moderate dimensions, very much smaller than the south Toroweap; yet this ravine descends rapidly and joins the river in the canyon bottom at grade. In this respect, it resembles the ravine in the northern esplanade east of the fault, already described. The lava-covered esplanade of the Uinkaret is seen north of the canyon: its enclosing Aubrey cliffs are almost completely hidden under the huge floods of lava that sweep down from a throng of vents on the plateau, and the floor of the esplanade is banked up to form an inclined plane. The lava cascades follow re-entrants of the esplanade border into the canyon, but are not distinctly traced all the way to the river. The cascades have a slope of 20° or 30°, while the upper half of the southern canyon wall has an average slope of 40° or 45°. The difference may be due to the abrasive or melting action of the lavas as they poured over the rim of the esplanade. The general effect of these unequal slopes is to give the canyon here an unsymmetrical cross-section. It is possible that the asymmetry may have been increased by the action of the lavas in pushing the river against its southern bank, and thus making it undercut the southern wall more actively than the northern; for the lower part (1500 or 2000 feet) of the wall has a slope of 65° on the south and rather under 60° on the north. The river itself is seen for a long mile of apparently placid flow: it is here as further east bordered by talus rather than by bare rock; patches of whitish sand lie on the banks here and there, and a few fan-deltas project from side ravines a third or a half way across the river. Beyond the terminal corners of the north and south esplanade of the Uinkaret block in the middle distance, there are glimpses of the Shivwits plateau, dropped a thousand feet from the corresponding upland surface of the Uinkaret. The view is closed by a long mesa surmounting the Shivwits, apparently a lava-capped mass of Permian beds.

The Hurricane Fault.

PREVIOUS STATEMENTS. — The Hurricane fault is, according to Dutton, like the Toroweap fault of modern date, younger than the beginning of the canyon cycle: the evidence for this conclusion being the relatively small retreat of the great cliffs of Aubrey limestone known as the

"Hurricane ledge" from the fault line. A more remote date seemed to me proved by the great recession of the Shinarump and Triassic cliffs in the higher (Uinkaret) block east of the fault than in the lower (Shivwits) block west of it: I was indeed led on my first excursion to believe here as elsewhere that the faulting had taken place long before the occurrence of the uplift by which the canyon cycle was introduced, so that the obliteration of the initial relief due to faulting and the general baselevelling of the plateau area had been accomplished before the erosion of the canyon was begun. According to this view, the Hurricane ledge as a topographic feature is not the direct result of faulting, but the result of renewed erosion on a faulted, baselevelled, and uplifted mass.

The work of last summer showed, in effect, that both these suppositions are in a measure correct; for the Hurricane fault has suffered repeated displacements, a long interval having elapsed between its earliest and latest movements. The relief produced by the earliest displacement was demonstrably obliterated over a large area before the later displacements occurred: while the relief produced by the latest displacement is still in certain places but little affected by erosion.

The remote date of the earliest displacement is proved by the great amount of erosion that has taken place after it. This is shown first by the retreat of the escarpments in the uplifted (Uinkaret) block several miles in excess of their retreat in the other (Shivwits) block, and second by the continuity of a level lava flow resting on an even surface of erosion that crosses the fault line. The first line of evidence was presented in my previous essay (b, p. 142–148); the second may be introduced here.

THE SECTION NEAR COAL SPRING. — A ride of some ten miles west-southwest of Mt. Trumbull carries one to a point near Coal spring, about eighteen miles north of the canyon, where the western escarpment of the Uinkaret plateau is capped with a lava bed, whose essential features are shown in the front block of Figure 8. The escarpment at this point is of moderate slope, quite different from its usual bold form; and instead of consisting of a cliff of upper Aubrey above a talus-slope of lower Aubrey, as is the case for most of its length further north, the escarpment here shows abundant outcrops of gray and reddish Permian clays, one thousand feet or more in thickness.

These Permian beds evidently belong in the western or Shivwits block, where they follow normally above the yellowish super-Aubrey beds which to-day constitute so much of the surface of that block below the

Hurricane ledge. The Permian beds stand, however, opposite to the lower and upper Aubrey beds in the Uinkaret block. The Hurricane fault in this locality must therefore pass underneath the lava bed, and its throw must be at least a thousand feet. The effect of faulting, without erosion, is shown in the back block of Figure 8. At a later time when the lava was erupted, erosion of the faulted mass must have progressed so far that the Permian clays had been largely removed from the Uinkaret block hereabouts, while they still largely remained on the Shivwits, so as to make a level surface across the fault line on which the lava

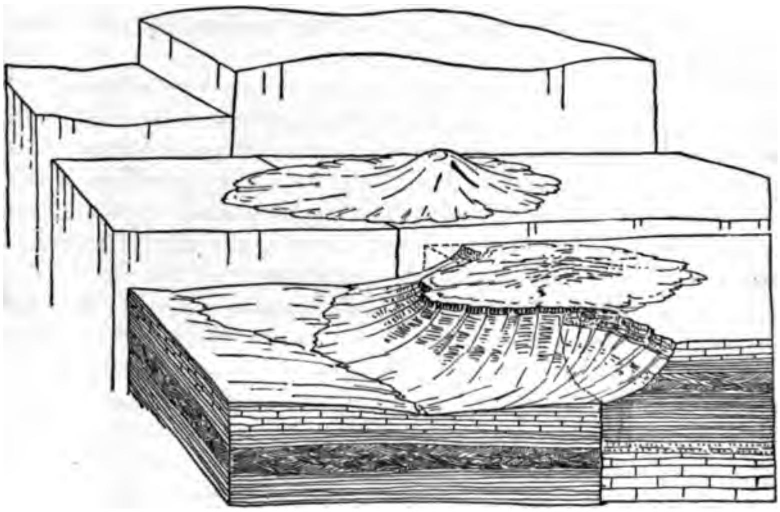

FIGURE 8.

Diagrams to illustrate the history of the Hurricane fault near Coal spring. The back block shows the effect of faulting without erosion. The middle block shows a volcano erupted near the fault after the faulted mass had been worn down to a peneplain. The front block gives a generalized view of existing conditions produced by uplift and erosion of the middle block.

was poured out, as in the middle block of Figure 8. It is evident that such a correspondence of level across the fault on beds of very unequal resistance could have been produced only by long-continued and widespread erosion when the region stood much lower than now. This structure may therefore be taken as another point in the evidence that demands two cycles of erosion (the plateau cycle and the canyon cycle) for the physiographic development of the region. The chief movement of the Hurricane fault must consequently be dated far back in the plateau

cycle of erosion, and this makes the Hurricane fault as old as the Sevier-Toroweap fault.

The point from which these observations were made is not surely identified on Dutton's map, but it is probably the basalt-capped bluff at lat. 36°22½′, long. 113°16½′, on Atlas sheet VIII. The lava-capped Permian slope lies just beyond a ravine next north of the bluff, from half a mile to a mile distant, and quite unmistakable as to structure; but on Dutton's map the corresponding slope is colored to show a slanting sheet of basalt, and it is especially on this account that I am uncertain as to its identification.

An important corollary of the above conclusion regarding the date of the fault is that when a general uplift of this broadly eroded region took place, introducing the canyon cycle, the renewed work of erosion was not limited to the carving of the canyon alone; it must have included the sweeping of weak strata such as the Permian clays from wide areas, as was indicated in my previous essay (b, p. 136). If the history of the region is thus correctly interpreted, the present inequality of level between the Shivwits and the Uinkaret plateaus is only very indirectly the result of faulting. It is directly the result of erosion by which a heavy mass of weak Permian clays has been quickly worn off of the Shivwits plateau, while only a small amount of carving has been accomplished in the resistant Aubrey beds of the adjoining Uinkaret plateau. The Hurricane ledge is therefore a cliff developed by erosion on a faulted mass, as in the foreground of Figure 8; it is not a "fault cliff" in the proper sense of that term, except in so far as modern faulting, late in the canyon cycle, may have increased the escarpment of erosion. We were unable to recognize any such element in the view from the bluff near Coal spring: if modern movement has taken place in this locality, it can have hardly occurred on the ancient surface of dislocation, for the lava bed that crosses the fault line did not seem to be broken.

Renewed movement has, however, taken place elsewhere in association with the Hurricane fault. Dutton states that certain modern lava beds are somewhat dislocated on a branch of the Hurricane fault in Quantoweap valley not far north of the canyon (b, p. 116, 117), just as they are at the mouth of south Toroweap valley. But much greater modern movement, long after the strong ancient movement, has taken place seventy miles north of the canyon where Virgin river crosses the fault line and beyond, as will be fully set forth in the report by my companions, Messrs. Huntington and Goldthwait.

The great contrast in the resistance of different rocks to erosion may

be taken either as a postulate of this interpretation of the Hurricane ledge, or as a consequence following from it: in either case, the explanation of the plateau topography involves the recognition of two groups of rocks, very unlike in their resistance to erosion, so that a period of time which only serves for the erosion of a narrow canyon by a strong river in the more resistant strata, suffices for the stripping of the less resistant strata from great areas by unconcentrated subaerial weathering and by the washing of occasional wet-weather streams.

THE SECTION NEAR ANTELOPE WASH. — The Hurricane ledge and its fault would well repay attentive study along the western border of the Uinkaret plateau; but springs are so few and far between along its course that it is difficult of exploration. We rode out to its edge at two other points north of the lava-capped spur near Coal spring: one was near one of the northwestern volcanoes of the Trumbull area, an isolated cone about thirty miles north of the canyon; the other was a mile south of the trench cut by Antelope wash. From the first of these points, we saw a high lava-capped Permian butte rising over the Shivwits plateau about three miles west of the Aubrey strata exposed in Hurricane ledge. This seems to confirm the conclusion reached near Coal spring; for the lava-cap suggests that the underlying Permian strata have an approximately level surface at an altitude that is far above baselevel to-day, but which must have been relatively near baselevel before the lava was poured out; otherwise the Permian surface could hardly have been worn so flat as it seems to be. A local complication was here noted at the base of the ledge, strongly suggestive of recent faulting, but we had no time to descend and study it.

The view northward showed at a distance of ten or fifteen miles a curious offset in the fault whereby a splinter of upper Aubrey at the edge of the Uinkaret bends down and descends southward to the Shivwits level, as is roughly shown in Figure 9.

The view from the Hurricane ledge near Antelope was exceptionally interesting in its display of brilliant red Triassic clays and sandstones in the ten miles of lower land between the base of the ledge and the Virgin river east of St. George, and in its exhibition of lava-capped Permian mesas on the northern terminal slope of the Shivwits plateau. The geological wonders of the scene were rivalled only by its exceptional barrenness. Not the least notable feature was the suggestion of extreme heat given by the vivid colors of the Trias as well as by the ominous blackness of the lavas. A muddy stream was still running down the channel of the wash from the thundershowers of the afternoon before. The dis-

trict was plainly enough not one to tempt exploration in midsummer, but as it all lay within ten miles of Virgin river it might be comfortably examined in the spring or fall months. It will be briefly described by Messrs. Huntington and Goldthwait, but it would repay much more elaborate treatment than they were able to give it.

The Hurricane ledge near Antelope probably owes a good part of its height to modern movement on or near the plane of an ancient fault. The same statement may be made with more confidence of the point a mile south of Virgin canyon where my party descended the ledge in 1900, and of the point three miles north of the same canyon where we came down the wagon road from Virgin city to Toquerville last summer; but all this will be described by my student companions.

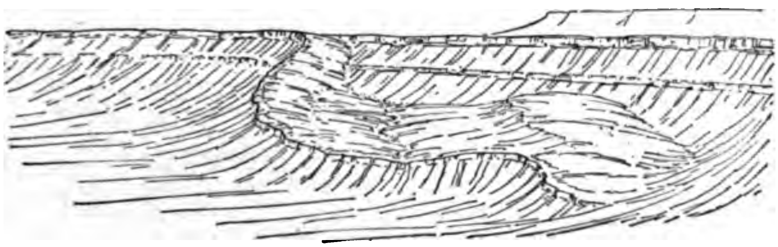

FIGURE 9.

Diagram of a rock-splinter on the Hurricane fault.

The Topography of the Colorado Canyon.

THE CROSS-SECTION OF THE CANYON. — The form of the Colorado canyon as seen in cross-section seems everywhere responsive to the resistance of the rocks in which it is carved. The river appears to have entrenched itself beneath the rising plateau with relative rapidity and continuity, there being no benches independent of resistant strata, and therefore no proof of pauses during the uplift of the region. The esplanade that forms so striking a feature of the canyon in the Uinkaret and in the western part of the Kanab plateau is accordant with the upper surface of the heavy sandstones that overlie the red-wall limestone in which the inner gorge is there cut. As was pointed out in my previous essay, the topographic maps of the canyon show a gradual disappearance of the esplanade eastward, and in the Kaibab portion of the canyon the stratigraphic equivalent of the esplanade is seen only in a series of thoroughly dissected red-wall spurs. The reason previously suggested

for this change is the weakening of the upper Tonto strata as they extend eastward. In the Uinkaret they are strong enough to act as cliff-makers with the overlying red-wall limestones; in the Kaibab they are a heavy series of relatively weak gray and yellowish shales by which the red-wall cliffs are undermined. The single bench shown in the cross-section of the canyon near Toroweap valley, Figure 10 A, is therefore replaced by two benches in the canyon of the Kaibab section, Figure 10 B, the lower bench being capped by the Tonto sandstone and cut by the narrow gorge in the fundamental crystalline rocks; the upper bench being held by the red-wall limestone. The gray slopes of Tonto shales between the benches are notable features of the canyon in the Kaibab.

It is interesting to note that in the eastern part of the canyon in the Kaibab, which I had opportunity of seeing in the superb view from

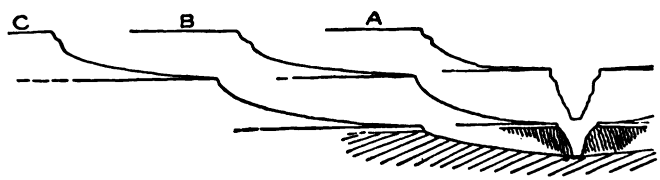

FIGURE 10.

Sections of the Colorado canyon at the Toroweap (A), in the middle Kaibab (B), and in the eastern Kaibab (C).

Bissell's point in 1901, the cross-section is still further changed, as in Figure 10 C; here the basal crystallines give way to relatively weak Algonkian strata, and the bottom of the canyon is a well-opened valley with some strips of flood-plain bordering the river here and there. Further up the river, where the east Kaibab monoclines bend down all the basal crystallines and Algonkians beneath the canyon bottom, the red-wall limestones close in again to form the Marble canyon. Still further up at Lee's ferry, where the red-wall limestones dip underground and bring the weak Permians and lower Trias down to the river, the canyon is for a short distance replaced by an open valley. Then the hard Trias cliffs close in to form Echo canyon. The accordance of form and structure is thus found to be so close that it seems inadmissible to accept the esplanade, a local feature in the western part of the canyon, in proof of a pause in the general uplift of the whole region. Had such a pause occurred, there should be other evidence of it besides the esplanade.

AMPHITHEATERS IN THE CANYON WALLS. — Many of the sharp spurs into which the red-wall cliffs are now cut in the Kaibab portion of the canyon are separated by amphitheaters of remarkably regular curvature. The explanation for these notable forms that occurred to me after having seen them in 1900 (b, p. 178) was fully confirmed in my excursion of 1901.

The amphitheaters occur only where the area whose drainage falls from higher levels over the cliffs is so small that it does not supply any large streams even in wet weather. In the absence of large streams, all parts of the red-wall cliff in each amphitheater now retreat, and indeed for a long time have retreated, at about equal rates. For example, the red-wall cliffs of the amphitheaters, G and J, in the spur

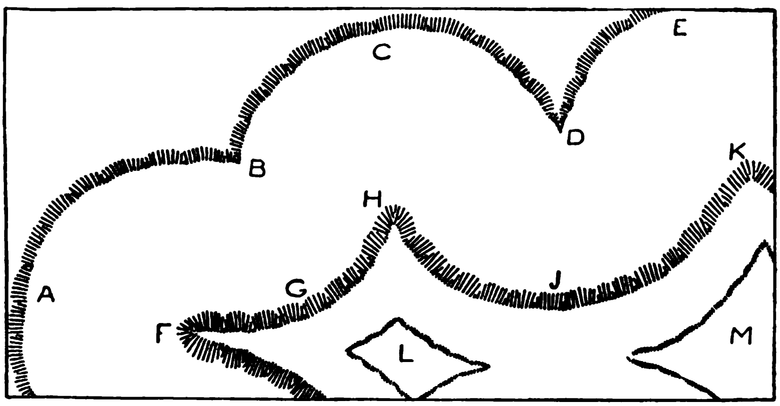

FIGURE 11.

Diagram of amphitheaters and cusps in the wall of the Colorado canyon.

of Figure 11, receive drainage only from the short slopes of isolated lower Aubrey outliers, L and M; all parts of the cliff face therefore retreat about equally. The curved cliff face, G, is an arc whose center lies near the point, B, this point being the site of a re-entrant in the cliff face at that stage in its earlier history when its rate of retreat in the re-entrant was but little faster than that on the adjoining convex spurs A and C. The curves of these former convex spurs are likewise arcs whose centers are roughly indicated by the apices of the present sharp spurs, F and H, that now separate the amphitheaters. In other words, amphitheaters are forms into which the acutely re-entrant ravines of earlier stages systematically develop as the cycle of erosion progresses;

similarly, the sharp cusps between the amphitheaters are the later stages of the round fronted spurs that once separated the ravines.

THE PROFILE OF SHARP CUSPS. — When the red-wall spurs are sharpened into slender cusps all the overlying Aubrey strata are removed. The cusps are then unprotected by waste from above, and they are attacked on both sides by the weather. Under these conditions, the relatively even edge of the cliff in the amphitheater is exchanged for a serrated crest line, a true arête. Again when two amphitheaters head against each other, the isthmus of cliff wall between them is gradually narrowed and converted into an arête that sags in the middle. Arêtes in Alpine mountains occupy similar positions, but there the amphitheaters are usually cirques of glacial origin, as Richter and others have shown.

The strong color of the red-wall cliffs in the amphitheaters is due to staining by wash from the overlying lower Aubrey red beds. Where the serrated cusps stand forth, stripped of the Aubrey cover and out of the way of descending wash, the cliffs are gray.

It has been suggested to me by a correspondent, well versed in the topography of arid regions, that the amphitheaters of the canyon walls are more largely the product of wind action than would be inferred from the explanation here given for them. Certainly the wind is a powerful agent in regions where vegetation is as scanty as it is on the barren walls of the Colorado canyon, yet I cannot think that wind action is largely responsible for the amphitheaters, inasmuch as their slopes are always developed in accordance with lines of gravitative action and not in sympathy with the flowing lines characteristic of the bottom of an air current. The winds must often enough sweep the finer detritus about, yet its general disposition is essentially such as creeping and washing waste should assume. So with the regularly concave amphitheaters: under the control of wind action these forms might occur at various altitudes, irrespective of tributary slopes at higher levels. As a matter of fact, the concave amphitheaters are developed only in particular situations with respect to the wash of waste from higher levels, and therefore, however active the wind may be in shaping them, its activity must be subordinate to that of local weathering and of the down-slope movement of waste under the control of gravity.

GENERAL RELATIONS OF AMPHITHEATERS AND CUSPS. – The correctness and generality of this view as to the origin of the amphitheaters and cusps are sustained by several lines of evidence. In the first place, the earlier forms, from which the cusps and amphitheaters of the red-wall

in the Kaibab have been developed, are now imitated in the red-wall of the western part of the canyon in the Kanab plateau; here the progress in widening the canyon and in the accompanying sculpture of its walls has been relatively retarded by reason of the resistant nature of the whole Tonto formation, as has already been pointed out. The rim of the esplanade, which overlies and closely follows the pattern of the red-wall cliffs, repeatedly advances in great rounded promontories and recedes into sharply re-entrant ravines: amphitheaters and cusps of the Kaibab type are here unknown at the red-wall horizon. They are, however, already fairly well developed in the higher horizon of the resistant upper Aubrey beds, whose cliffs enclose the esplanade. The Aubrey cliffs, sapped by the weak lower Aubrey red beds, have here been worn back about as far from the axis of the canyon as the red-wall cliffs have been in the Kaibab; and the two are therefore in similar stages of development. As a rule, however, the Aubrey is traversed by too much drainage from the Kanab uplands for the development of perfect amphitheaters, although it shows sharp cusps at several points.

In the second place, the bench of Tonto sandstone in the Kaibab section exhibits rounded spurs and sharp ravine re-entrants where its dissection has been retarded in virtue of the resistance of the fundamental crystalline rocks that underlie the greater part of its extent; but on passing eastward beyond the apex of the "wedge," to the district where the Tonto is underlaid by the relatively weak Unkar series, dissection is much further advanced, and here the Tonto exhibits sharp spurs and concave amphitheaters that closely resemble those of the red-wall in the district already described; while the red-wall itself is reduced to slender buttes and pinnacles of small area, or altogether consumed. The various forms through which the cliff faces run are therefore evidently developed in systematic order.

In the third place, there is no need of a succession of resistant and weak strata for the production of the patterns outlined in Figure 11. All that is necessary is a mass that shall not possess horizontal diversity of structure by which the development of subsequent streams is guided in particular directions. Given a mass of horizontal or of homogeneous structure in which a drainage system with its branchwork of master and minor streams is in process of development: its contour lines must assume in due order all the patterns given in Figure 11. Not only so; the contour lines of the sculptured mass at mid-stage in the cycle have a certain historic value; those at lower levels exhibit the pattern from which the contours of the higher levels have been evolved; those at higher levels

predict the pattern which many of the lower ones will in time attain. Some of the contours may gain an increased emphasis from following the outcrops of cliff-making strata; thus they catch the eye more readily than others which lie on evenly graded slopes; but all exemplify the same general principle. In the absence of strong cliff-makers, the high-level contours of spurs and isolated outliers will not assume the pattern of acute cusps; they will be rounded at their convex turns by the process of soil creeping, just as the crest-line divides are rounded; but in general the high-level contour lines in young or maturely dissected plateaus will show large re-entrant curves between relatively sharp salients (the sharpest salients or cusps occurring on contours that follow the outcrop of a cliff-making stratum), while the contours at low levels will show large salient curves between relatively sharp re-entrants (the sharpest re-entrants occurring on contours that follow a cascade-making stratum in an early stage of the cycle of erosion).

The Great Terraces.

Refreshed Cliff Profiles. — In my former report, it was stated regarding the great mesozoic escarpments or terraces, north of the canyon: "The sharpness of the cliffs is highly suggestive of aridity, but a relatively short arid period would suffice to sharpen the cliff profiles, even if they had been somewhat dulled by a previous humid period" (b, p. 188). This opinion needs a supplement concerning the change in the appearance of the escarpments that would accompany the

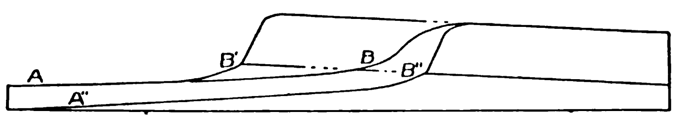

Figure 12.

The changing profiles of retreating escarpments.

transition from the subdued forms appropriate to a late stage of the plateau cycle, to the refreshed forms appropriate to the present young stage of the canyon cycle.

In the later stages of a cycle of erosion in a region of nearly horizontal structure many escarpments may have retreated far back from the main waterways. The graded floor of the peneplain of degradation, A B, Figure 12, may then ascend gently to such an altitude at the base

of the escarpment, B, as to stand there above the level of the weak strata which underlies the strong escarpment maker. Under such conditions, the future retreat of the escarpment will be relatively slow, and its aged form must therefore be less abrupt than at an earlier stage of the cycle when the graded floor, A B′, rose only midway in the mass of the weak strata; for at this earlier stage, the retreat of the escarpment must have been accelerated by the sapping of its base, and it must then in its vigorous maturity have had a bold and constantly refreshed face.

Now if the aged region enters a new cycle of erosion, in consequence of broad uplift, the main river quickly erodes a canyon and already in the youth of the new order of things will be found at a significant depth beneath its former channel. In due time, the side streams will entrench themselves beneath the peneplain of the former cycle; a new graded floor A″ B″ will be opened with respect to the streams, and the subdued cliff will be actively attacked as the weak strata beneath the cliff-maker are worn away; the cliff will thus be again steepened or refreshed.

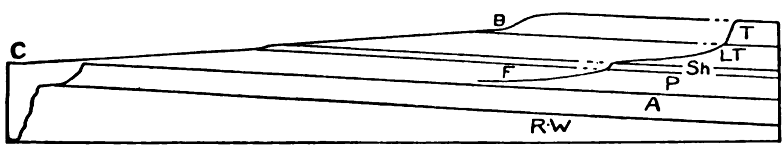

FIGURE 13.

Generalized section of the plateau from the Colorado canyon to the Vermilion cliffs near Pipe spring. Abbreviations: — R. W., Redwall limestones; A, Aubrey group; P, Permian; Sh, Shinarump sandstone; L T, Lower Trias clays; T, Triassic sandstones.

Inasmuch as the Colorado canyon is to be explained as the result of a new attack of erosive forces on an uplifted peneplain, there seems to be equally good reason for explaining also the bold cliffs in which the strong Mesozoic strata outcrop north of the canyon as the result of a revival of erosive forces on the subdued cliffs that once bordered the peneplain. It is not possible at present to determine the amount of retreat that the cliffs have suffered in the renewed attack made upon them in the canyon cycle; but in the case of the Vermilion cliffs at Pipe spring the retreat is likely, it seems to me, to have been several miles at least. The reason for assigning so considerable a measure to the retreat of these cliffs is found in the probability already stated that a large volume of weak Permian and lower Triassic strata have been worn off of the plateau in front of the cliffs during the canyon cycle. At the beginning of that cycle, when the Colorado river, C, Figure 13, flowed at or above

the level of the upper Aubrey limestones, a gentle sloping surface, C B, over Permian and lower Triassic strata, in which the Shinarump cliff must have been nearly extinguished, is inferred to have extended from the river plain northward to the base of the faded Vermilion cliffs.

To-day, the plateau in the neighborhood of Fredonia and Pipe spring is a thousand feet lower than it is at the rim of the canyon. It is true that some of this difference of level may be attributed to an inequality in the uplift by which the canyon cycle was initiated; but the great altitude of the High plateaus further north does not encourage the supposition of less uplift there than in the south. It seems more probable that the lower surface by Fredonia and Pipe spring is due to the extensive erosion, during the early stages of the canyon cycle thus far elapsed, of a large body of weak strata, whose persistence to the close of the plateau cycle was due to their lying below the level at which streams could then attack them, and whose early removal in the current cycle is due to their being raised high above the level of active stream work. It should be remembered in this connection that good warrant for the abundant erosion of Permian clays during the canyon cycle has been found in the study of the Hurricane fault in the Trumbull district. Accompanying the removal of the weak strata in the Pipe spring district, there must have been a resurrection of the nearly extinguished Shinarump cliffs, Sh, and a refreshment of the subdued Vermilion cliffs, T. These bold forms, presenting to-day every indication of rapid retreat, are therefore to be associated with the Grand canyon as the work of very modern erosion on pre-existent forms of much weaker relief. How general this change may be I cannot say, but it may well include all the Shinarump escarpments in whose under slope the Permian clays are laid bare in sharp-cut ravines as in Plate 3 B, and all the ragged Triassic escarpments along which landslides have occurred as stated in my earlier essay (b, p. 121) in consequence of the recent removal of the weak lower Triassic clays: views of such escarpment are given in Plates 2 B, 6 A, and 7 A.

Revived Erosion of the Pink Cliffs. — The Pink cliffs of the Paunsagunt plateau did not fulfil the expectation that had been awakened by Powell's and Dutton's descriptions of them, probably because the southwestern border of the plateau that we saw is less precipitous than that on the southeast (Dutton, a, p. 254). In the thirty miles or more of the escarpment that we followed, it is only intermittently bare and pink; much of the front has a graded slope, green with forest trees. Cliffs of bare and precipitous rock occupy only about

half the length of the escarpment, as it is seen from the lava-capped hill where the Panguitch-Kanab road crosses the divide between Virgin river and Kanab creek; and all these cliff faces are evidently the result of a revival of erosion in the Kanab headwaters by which the tree-covered slope, formerly continuous, has been locally attacked and worn away. The once subdued escarpment has thus been here and there eroded back into cliff-walled amphitheatral recesses, whose pink faces are seen between the forest-covered slopes that still record an earlier stage of erosion.

The revival of stream erosion by which the Pink cliffs are thus locally refreshed may be associated with the revival of degradation by which the present graded floor of Upper Kanab creek has been lowered beneath the level of earlier grades, whose remnants may be clearly seen stretching southwestward beneath the outermost point of Paunsagunt plateau. Both these consequences of revival may be plausibly associated with the elevation of the region by which the canyon cycle was introduced; and the relatively small amount of work here accomplished in the new cycle as compared to the much greater work accomplished in the same period of time by the Colorado, the trunk river of the region, may be reasonably ascribed to the normal delay of small headwater streams in taking cognizance of uplifts, as compared to the promptness with which advantage is taken of such opportunities by the main rivers.

The upland of the Paunsagunt plateau is drained by the consequent northeast-flowing headwaters of the East fork of the Sevier. When the upland was first formed, the streams must have headed decidedly farther south than they do now; for they have been significantly shortened by the recession that the Pink cliffs have suffered during the excavation of Upper Kanab valley. The indentations in the scalloped sky line of the cliffs mark the present heads of these shortened streams.

THE VALLEY OF THE VIRGIN. — The towers and temples of the Virgin canyon in the Triassic terrace of the High plateaus have been described in glowing language by Dutton (b, Chap. III.). As in the Colorado canyon, the cross-section of the Virgin canyon exhibits a perfect response of form to structure, and an absence of benches independent of structure such as would be expected had there been a significant pause during the elevation in consequence of which the canyon has been eroded. At Rockville, a few miles below the junction of the North and East forks of the Virgin, the river flows in the middle Permian clays;

here the Shinarump sandstone forms a strong bench, back from which the huge upper Trias cliffs, Plates 6 A, 7 A, have retreated from two to four miles, in consequence of active sapping by the underlying weak lower Trias clays. The general profile is shown in ABCDE, Figure 14. In following up the North fork, the valley or canyon becomes narrower until it is hardly more than a cleft: this is the remarkable Mukuntuweap canyon of which Gilbert gave an account thirty years ago (p. 79) and of which we saw the entrance last summer; our own failure to enter it being due only to that oft-prevailing difficulty in geological excursions, a lack of time. The cleft has been given fame from the reproduction of Gilbert's figure of it on the back cover of Leconte's Elements of Geology, where it has often been mistaken for a section of the Colorado canyon. The open lower canyon of the Virgin here narrows to an enclosed cleft

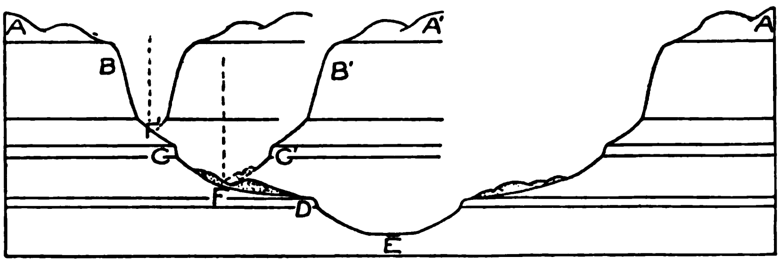

FIGURE 14.

Generalized cross-section of the canyon of Virgin river.

because the gentle northward dip of the strata combines with the northward ascent of the river bed to raise the stream from a mid-Permian to a mid-Trias horizon; here it finds only the heavy and resistant sandstone cliff-maker, B, almost free from partings on stratification surfaces, but well provided with vertical joints; as a result, the rocks at the canyon bottom exert no sapping action on those higher up the walls. The cross-section of the canyon at any intermediate point between Rockville and the cleft may be represented by imagining a vertical line at an appropriate position, as F, on the profile ABCDE, and reproducing the upper part of the profile, ABCF, on the right of the vertical, as A′B′C′F.

It is only at higher levels than those exposed in the deeper part of the Virgin canyon that traces are found of an older topography, formed in an earlier cycle of erosion than that in which the canyon as a whole

was eroded. Some account of the older topography will be given in the Bulletin by Messrs. Huntington and Goldthwait to be issued.

The huge landslides along the base of Echo and Vermilion cliffs east of the Kaibab were ascribed, in my previous essay, to an active sapping of the weak Triassic clays under the cliffs in consequence of the revival of erosive processes that followed the uplift of the Canyon cycle. Numerous landslides of similar stratigraphic position were observed during the past summer in the valley of the Virgin near Rockville. They are extensive and abundant, and large enough to appear in Plates 6 A and 7 A. It is a matter of surprise that they are not mentioned in Dutton's account of this district. Where the valley is broad, the slides lie for the most part on the Shinarump bench, as in Figure 14: they have the form of disorderly mounds and hills, from two hundred to six hundred feet high, strewn with huge boulders for which there is no local source in the form of immediately surmounting cliffs; indeed, some of the mounds stand one or two miles forward of the Triassic cliffs from which they were derived. One example was noted in which the front of a slide descended below the Shinarump cliff into a ravine worn in the Permian slopes beneath; and this slide has been utilized for the construction of the roadway from Canaan spring to Rockville, the Shinarump cliff being apparently impassable elsewhere for several miles up and down the valley. There appears to have been a significant amount of erosion since the slides took place, for their slopes seemed to be of greater uniformity than would likely have been the case in their initial disorder.

As one passes up the valley of the North fork, the Shinarump bench, Plate 7 A, gradually decreases in height and soon disappears under the valley floor. The landslides then advance directly toward the stream, and five miles further north they form a serious barrier in its course: here for a mile or more the channel is interrupted by bouldery rapids. The landslides then cease, because the weak clays by whose sapping they were caused have run under ground, and the valley floor has a flat flood-plain for two miles or more, apparently the result of alluvial filling caused by the landslides barrier below. The flood-plain is known as Zion; it is cultivated by the farmers who come up the rough road over the landslides from the villages down the valley. A mile further on, the stream bed rises above the shaly sandstones that elsewhere form a slope beneath the heavy upper Trias cliff-maker, and here the cliffs close in precipitously upon the stream, producing the cleft-like Mukuntuweap canyon, already mentioned. The rock walls of Zion, Plate 6 B, are

of wonderfully massive structure, steep, bare, and clean: they frequently show cross-bedding, but the texture of the sands is so uniform that there is little or no weathering along the bedding planes. The cliffs retreat by the detachment of huge slabs on vertical joint planes, but the amount of talus seems very small in proportion to the great height of the cliffs. Hanging lateral valleys open at various heights in the main valley walls; and above the level of the higher lateral valleys the cliffs rise in rounded domes, which seem to record a more mature stage of erosion during an earlier cycle, when the land stood lower than at present.

The rolling plateau country in which the canyon is incised was described to us as affording abundant pasture and timber. A zigzag path has recently been constructed on one of the more battered parts of the canyon wall: part of the path consists of tree-trunks held against the rock face by iron clamps and brackets. Cattle are here driven up to the highlands for summer pasture. A wire rope has lately been stretched from a bold cliff-top down into the valley, to serve for lowering boards and shingles from the upper forest. The height of the cliffs is so much greater than can be properly estimated that I refrain from indicating it in feet; but the rough units of measure should be thousands rather than hundreds.

The Fresh-water Tertiaries.

Previous Statements. — During the past summer I had opportunity of examining with some care several characteristic sections of the fresh-water Tertiary formations which occupy so large an area in the Cordilleran region. The localities to be described here are those of the Eocene beds exposed in the Pink cliffs of the Paunsagunt plateau and thereabouts in southern Utah, and the Green river beds near the town of that name in Wyoming. The object of this study was to consider on the ground whether the theory of the unqualifiedly lacustrine origin of these formations, presented in the various reports on the geology of the region, would command entire acceptance. The lacustrine theory has been, until recently, practically undisputed for thirty or more years, but a number of essays have now been published in which the capacity of aggrading rivers and of winds to form extensive non-marine deposits has been recognized, and in which the effort has been made to discriminate carefully between fresh-water formations of different origins. In a number of these essays, especially in those by Matthews, Hatcher,

Johnson, Merriam, and Calkins, the lacustrine theory has been definitely replaced by theories of fluviatile or æolian agencies, and at present there is evidently a strong tide of opinion turning from the unqualifiedly lacustrine origin of the various fresh-water Tertiaries; but in just what manner the unqualified lacustrine theory shall be amended or replaced is not yet apparent in all cases. Indeed, this aspect of the problem can be settled only by extended and detailed study in the field of each formation. It is essential in the prosecution of such study that a critical attention should be given to the deposits now accumulating in and around the basins of large and small, deep and shallow lakes, as well as on the flood-plains of large and small rivers; for at present one of the chief difficulties of the problem comes from a lack of knowledge regarding the characteristic minute structures of such deposits. Truly the day is passing when coarse conglomerates and cross-bedded sandstones can be described as of lacustrine origin without leaving some doubt in the mind of the geologist who reads so undiscriminating a description; but the day has not yet come when even-bedded, fine-textured strata are habitually and critically examined to learn whether they are of lake-bottom or of flood-plain origin.

It is confidently believed that one of the best aids towards the solution of the class of problems here considered that an observer can carry with him into the field is a careful analysis of the many possible conditions under which continental deposits may accumulate. It is in particular important to recognize on the one hand the very fine and uniform deposits that should characterize the central area, and the coarse deposits that should accumulate around the marginal area of long-enduring lakes of large area and considerable depth, with their shores close against the base of encircling mountains; and on the other hand the very variable deposits that should characterize short-lived, fluctuating lakes of small area and slight depth, with ill-defined shores on gently sloping fluviatile plains of piedmont waste. With such an analysis in mind, the observer is likely to find it difficult to reconcile the theoretical conditions suggested by such phrases as a "lake of vast dimensions" and "the great Eocene lake" with the variable deposits that prevail in many of the Tertiary basins.

EOCENE OF THE HIGH PLATEAUS OF UTAH. — Our route to the head of Sevier river, south of Panguitch, and thence over the low divides to the headwaters of the Virgin river and of Upper Kanab creek and to the Pink cliffs of the Paunsagunt, led us past many excellent exposures of the Eocene, described by Howell and Dutton. The refreshed faces of the

Pink cliffs exhibit an unusually fine section from the brown shales and sandstones that we took to be upper Cretaceous up to the pink-stained white limestones of the Eocene. The Cretaceous, outcropping abundantly on the sides of the valley by which the cliffs were approached from Upper Kanab, consists of brown and gray muddy sandstones and shales, abundantly cross-bedded. How far this formation should be classed as marine because some of its beds contain Ostreas, or continental because other beds include coal seams, remains to be determined. The uppermost brown beds, in the slope under the cliffs, are overlaid by about fifty feet of fine-grained reddish beds; "reddish mud" suggests their original condition. These are separated from the next higher members of the series by a gently undulating surface of unconformity. Then come about twenty feet of fine cross-bedded sandstone, followed by more evenly bedded strata which seemed to merge upwards into a fine, evenly bedded or massive white sandy limestone, whose cliff face is stained a more or less vivid pink where the drainage from the upland washes over it, but which has a creamy white color in the more isolated promontories and pinnacles. The lacustrine origin of these beds, which contain fresh-water mollusks according to Howell (p. 267–274), does not seem open to question so far as the limestones are concerned, but several purplish partings, a few feet thick, occur within the limestone series, and this variation of the beds does not seem consistent with the theory of their deposition in a vast lake. The partings are not continuous, but are seen to thin and end as they are traced a few hundred feet along the embayment in the cliff face that we visited. Howell said of the formation in general: "These Tertiary beds are so extremely variable in lithological character and thickness, that it is difficult to correlate sections, even when taken only a few miles apart, save in a very general way. This is especially noticeable in comparing sections near the western boundary of the system . . . while the eastern sections show more uniformity" . . . (p. 266).

The strata exposed in the hills near and at the divide between the Sevier and the Virgin are higher in the series than those in the Pink cliffs. Here we saw impure whitish or creamy limestones, sometimes evenly bedded, sometimes with wrinkled layers (as if locally disturbed by change of volume between unchanged under and overlying layers), sometimes without apparent stratification; but the limestones are associated with cross-bedded sandstones, both below and above, and with occasional reddish beds. The cross-bedding of the sandstones occurred in layers usually less than a foot in thickness, and showed rapid varia-

tions in distances of four or five feet. Well-defined outcrops of these sandstones, five or ten feet thick, weakened and disappeared when followed for a few hundred feet along a hillside. This was especially well seen on a slope just north of the Sevier-Virgin divide, where it could be explained only by the thinning out of the sandstone itself. On the divide and over some of the hills near it, we found the residual pebbles of a conglomerate that might probably have been discovered in place in localities where somewhat higher strata still remained intact.

Whatever share may have been taken by lakes in providing a site for these various deposits, it seems evident that the persistent existence of a single, large, continuous water body does not supply the conditions necessary for the accumulation of strata in which variations of composition, texture, and structure are so common.

THE GREEN RIVER BASIN, WYOMING. — The following notes on this interesting district are based on two half-day walks over the hills north and east of Green River station, Wyoming, supplemented by observations on natural outcrops and railroad cuts from passing trains.

The "paper shales" at Green river have often been instanced as proving the lacustrine origin of the formation of which they constitute so large a part, and it was with the special object of examining them closely that I made a short stop at this point on the Union Pacific railroad. The cut where most of the fossil fish have been found is now, I was told, filled in the new grading of the railroad, but many excellent sections of the formation are exposed in the dry ravines that dissect the barren slopes of the uplands through which Green river has here opened its valley. The outcrops are especially clear on the slopes towards which the river has lately swung, thus causing an entrenchment of the lateral water-courses and a stripping of the loose waste that tends to accumulate on those slopes from which the river has moved away. The best example of this kind that I visited was from a quarter to a half mile southeast of the point where the railroad leaves the river to turn eastward up the valley of Bitter creek, a mile or more east of the station. The lowest beds here seen are whitish shales with some partings of fine sandstones, about one hundred feet in total thickness. These are capped by a stronger sandstone, dull greenish brown in color, commonly showing cross-bedding, and varying in thickness up to about fifteen feet. The outcrops of this sandstone on both sides of Bitter creek valley determine a more or less continuous bench. As the strata here dip gently westward, the sandstone disappears underground a little west of the mouth of Bitter creek, so that it outcrops only near the base of the bluff north-

east of the town. In the abundant outcrops south of Bitter creek it was seen to be made up of lenticular deposits, whose groups of oblique beds rapidly vary in thickness. Neighboring sandy strata frequently exhibit a lenticular and cross-bedded structure on a small scale, in strong contrast to the even-bedded deposits of the paper shales, or cardboard shales as I should prefer to call them. In one exposure, a layer of sandy shale four feet thick has been obliquely cut out in a distance of eighteen feet, and the excavated space was filled in with innumerable little lenses and cross-beds. In another exposure, a series of somewhat concretionary, somewhat lenticular beds is cut out to a depth of two feet in a length of five, and the cavity is filled with rather even layers, followed by finely lenticular beds; the surface of local unconformity has in this latter instance a maximum dip of 30°. For a hundred feet or more over the sandstone bench, there are frequent alternations of gray cardboard shales with whitish calcareous and gray sandy layers, whose wasting outcrops supply the slopes with abundant slabs, large and small. The shales are of a remarkably even and continuous stratification, for which a lacustrine origin seems eminently appropriate, and a fluviatile origin on a broad flood-plain hardly less so; but the frequent alternations of the shales with layers of other kinds indicate equally frequent variations in the form or depth of the parent water-body, whatever it was. Some of the varying beds are greenish marls, with no distinct stratification in layers three or four feet thick. The sandstones are gray while in place, but weather brown as they creep down hill: some of the slabs show regular ripplemark, with crests from two to four inches apart; others are unevenly rippled and pitted; many of the layers show fine cross-bedding; a few contain rounded fragments of shale. Various samples are shown in Plate 7 B. Some of the calcareous beds have their layers separated by thin and variable clay partings which thicken up to a quarter or half inch, and then thin out in eight or ten inches. Other calcareous layers are seen, when weathered, to consist chiefly of fine pebbles well cemented, though this structure might not be suspected from a surface of fresh fracture: the constituent pebbles and grains, up to quarter or half an inch in diameter, are usually well rounded; they are often soft and clayey. The best specimens of this kind were found in the bluff northeast of the town. Their resemblance to certain specimens of tepetate, brought by Mr. R. T. Hill from the arid southwest, is very striking. The continuity of stratification in these variable deposits is noteworthy. Bands of lighter and darker color may be traced for several miles on the northern slopes of Bitter creek valley. On the

other hand, there must be frequent minor lapses of continuity, for the thin sandstone beds are certainly more common on some slopes than on others not far away at the same horizon. It should be noted in this connection that no one yet has carefully determined the degree of continuity that may prevail in the deposits of overflowing aggrading rivers.

The higher members of the shales and the whitish calcareous beds show fewer variations of structure than those beneath. They are succeeded by fifty feet or more of inconstant deposits that vary from paper shales to cross-bedded sandstones, increasingly changeable in composition, texture, thickness, and color. Some of these upper sandstone beds wedge out from five feet to nothing in a distance of fifty feet. Then come the capping bluffs of variable brown sandstone from forty to sixty feet or more in thickness, frequently of even texture and massive beds; again showing pronounced cross-bedding on a large scale. In the well-known butte that forms so conspicuous a landmark north of the town, there are local deposits of a bluish clay, twenty feet or more in length, yet hardly an inch in thickness, contained in the sandstone. In spite of the strength frequently attained by these capping beds, and in spite of the bold face which their outcrops often possess, the bluffs which the outcrops form are by no means continuous. They occur chiefly in promontories and on isolated buttes, along the margin of the less dissected upland that here borders the valleys of Green river and its larger branches. The re-entrants between the promontories are frequently of evenly graded slope without any strong capping sandstone bluff. In other districts of the west, the continuity of a rimming bluff formed by a hard horizontal layer as it contours around spurs and into ravines is of common occurrence, and for that reason the discontinuity of the bluffs around Green river very strongly suggests the discontinuity or at least the great variability of the bluff-making sandstones. Thus interpreted, the bluffs of the promontories and isolated outliers must mark local thickenings of the sandstone in the mass of weaker shales. It seems evident that if the cardboard shales are accepted as the deposits of a lake, the variable bench — and bluff — making sandstones must be of some other origin.

Bridger and Vermilion Creek Tertiaries. — The Union Pacific railroad between Green river and Weber canyon crosses broad areas of the Bridger and Vermilion creek formations. Natural outcrops are abundant for much of the way, and many artificial exposures are seen in the cuts along the track. Observation from an express train cannot be detailed, but it suffices to prove that the strata of these formations often

depart very far from the fine-grained, even, and thin-bedded deposits that are appealed to in the Green river formation as convincing evidence of lacustrine origin. In the Bridger area, there are abundant alternations of shales and sandstones; in the Vermilion creek area, of sandstones and conglomerates. Many of the beds are visibly lenticular and local, implying rapid variations in the conditions of origin, horizontally as well as vertically. But there is little new in all this, so far as facts of structure are concerned. Many details of structure are accurately stated in the reports of the Fortieth Parallel Survey. For the Bridger formation, we read: along the line of the railroad the lower members of the formation are seen "consisting of thin-bedded drab and greenish sandstones and clays" (ii. 245). North of Echo canyon, the Tertiaries consist "chiefly of red sandstones containing some fine shale and clay beds, and limited sheets of conglomerate" (ii. 331). It is chiefly to the interpretation rather than to the record of the facts that renewed analytical discussion should be directed.

It was perhaps natural at the time that the early western surveys were undertaken to class all fresh-water basin deposits as lacustrine; but the thirty years that have elapsed since then have as naturally introduced new interpretations. The unanalyzed, undetailed theory of wholesale deposition in a series of great lakes now seems to be entirely untenable for many of the fresh-water Tertiary formations of the Rocky Mountain region. The fine calcareous shales of the Green river formation strongly suggest deposition in standing water; but the associated cross-bedded sandstones imply an activity of movement in the depositing agent such as would characterize a stream rather than a lake. The heavy, coarse, and variable conglomerates of the Vermilion creek formation suggest deposition by running water; there seems to be no local indication of lacustrine conditions. The real need here is a resurvey of these formations, in which the facts shall be interpreted in view of all possible conditions of deposition.

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EXPLANATION OF PLATES.

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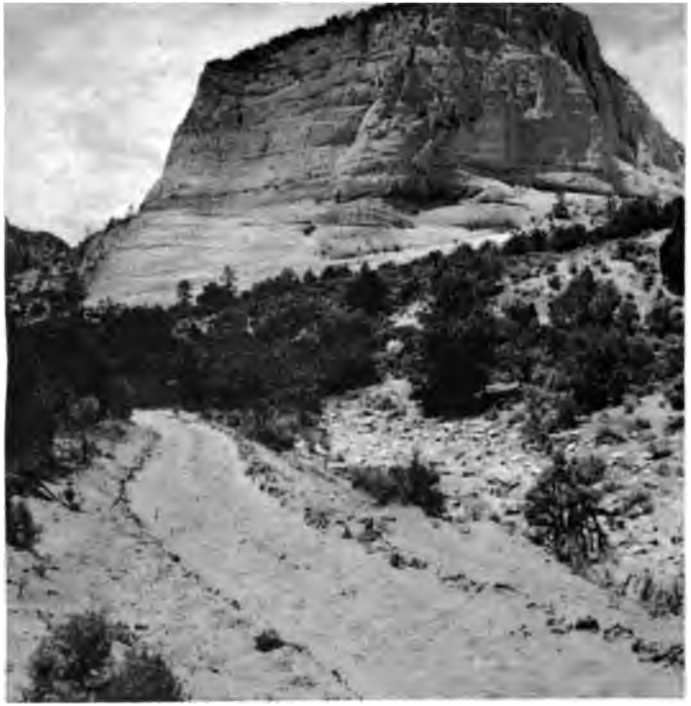
1 A. An outlier of the White cliffs; Jurassic sandstone next west of Kanab creek.
1 B. Detail of the base of Plate 1, showing cross-bedding.
2 A. Detail of cross-bedding in Jurassic sandstones, west branch of Kanab creek.
2 B. Vermilion cliffs: Triassic sandstones west of Pipe spring.
3 A. Sevier Fault at Pipe spring: looking north. In middle distance, the Shinarump bench, coming from the east, is cut off by the fault. The Triassic cliffs follow in the background. On the left, the Triassic cliffs stand in the middle distance beyond Moccasin valley.
3 B. Shinarump mesa with Permian slopes, between Antelope wash and Canaan gap.
4 A, B. The south wall of the Colorado canyon from the northern esplanade east of the Toroweap fault. The two views overlap slightly. Two ash cones lie on the esplanade in Plate 4 B.
5 A. South Toroweap valley, from the southwestern corner of the northern esplanade. The uplifted esplanade sandstone at the left margin is the same stratum as that of the general level of the valley floor. The cliffs in the central foreground are capped with lava: a small ash cone lies on their edge to the right.
5 B. Looking down the Colorado canyon from Vulcan's throne. Lava sheets form the slopes on the right. The Shivwits plateau is seen in the distance.
6 A. The "West Temple": Triassic cliffs over the Shinarump bench, valley of the Virgin at Rockville. Landslide masses at base of the cliffs.
6 B. The Cliffs of Zion, Mukuntuweap canyon; Jurassic and Triassic sandstones.
7 A. Looking southeast across the valley of the Virgin at Rockville from the Shinarump bench. Many of the hills on the Shinarump bench on the further side of the valley are landslides that have run forward from the Triassic cliffs in the background.
7 B. Slabs of sandstone from the Green river Tertiaries, Wyoming.



A. AN OUTLIER OF THE WHITE CLIFFS.

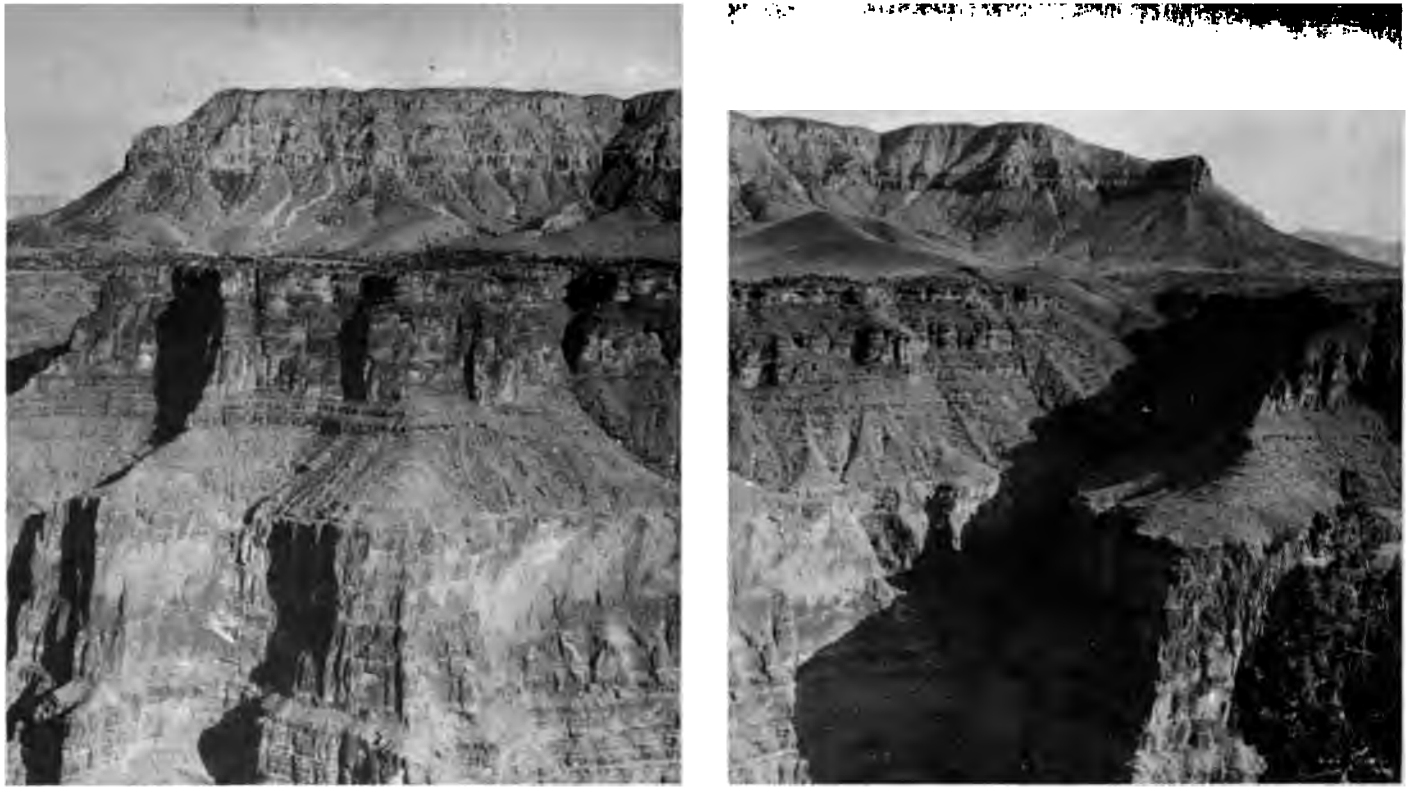
B. CROSS BEDDING IN THE WHITE CLIFFS.

A. CROSS BEDDING IN THE WHITE CLIFFS.

B. VERMILION CLIFFS NEAR PIPE SPRING.

A. THE SEVIER FAULT NEAR PIPE SPRING

B. A MESA OF SHINARUMP SANDSTONE ON PERMIAN CLAYS



A. B.

SOUTH WALL OF THE COLORADO CANYON.

A. SOUTH TOROWEAP VALLEY.

B. DOWN THE COLORADO CANYON FROM VULCAN'S THRONE.

A. SOUTH TOROWEAP VALLEY.

ILCAN'S THRONE.

A. WEST TEMPLE, VALLEY OF THE VIRGIN.

B. CLIFFS OF ZION.

A. ROCKVILLE ON THE VIRGIN RIVER.

B. RIPPLED SANDSTONES IN THE GREEN RIVER FORMATION.

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THE CHEMICAL COMPOSITION OF LIMESTONES FROM UPRAISED CORAL ISLANDS, WITH NOTES ON THEIR MICROSCOPICAL STRUCTURES.

BY ERNEST W. SKEATS.

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No. 2.— *The Chemical Composition of Limestones from Upraised Coral Islands, with Notes on their Microscopical Structures.*[1]

By Ernest W. Skeats.

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I. Introductory.

Since Darwin's historic voyage in the "Beagle" nearly seventy years ago, and Prof. J. D. Dana's work in connection with the United States Exploring Expedition (Wilkes) of 1838–42, perhaps no two subjects of geological interest have excited more attention and aroused more discussion than the question as to the origin of coral reefs and the problem of the formation of dolomite.

The work of subsequent investigators, especially that of Sir John Murray, in connection with the Challenger Expedition, has considerably increased our knowledge of the conditions under which coral reefs may be formed.

Within the last five years interest in this subject has been still further stimulated by several expeditions to localities in the Pacific and Indian oceans, which have been made with the object of extending our information as to the structure and origin of coral islands and to throw light on other problems related to this important question.

The expeditions to the Funafuti Atoll (1897–99) under Professor Sollas, and later under Prof. Edgeworth David, were organized by

[1] Reprinted with additions from the copy privately issued in 1902.

a Committee of the Royal Society, acting in conjunction with the Geographical Society of New South Wales. A boring was made through the rim of the atoll and this eventually reached a depth of 1114 feet.

The results of the inquiry are not yet published, but there is no doubt that they will be found to be of great interest and importance, both in connection with the question of the origin of coral reefs and also in their bearing on the formation of dolomite.

Methods of collecting Specimens. — In the Funafuti Expedition a boring was made on the edge of the reef, and a vertical succession of specimens was thus obtained. In that case, if the boring was in solid reef throughout, the position of a particular specimen determined its age relatively to those above and below it. This method of collecting has the further advantage that where a gradual structural or mineralogical change occurs in the rock, the change can be closely followed by specimens at short intervals, but its great cost renders it of only limited application. In the case of collections from raised coral reefs much the same result was sought by collecting in vertical sequence from cliff faces, ravines, etc., at heights definitely ascertained by measurement or by the records of the aneroid barometer.

During the upheaval of a coral island accretions to the older rocks occur, to a greater or less extent, in the form of fringing reefs, several of which are often found at successive heights on one island, marking pauses in the movement of elevation.[1] Stalagmitic deposits and talus slopes also occasionally mask the true surface of a cliff face. On this account it is necessary to exercise great caution in collecting from raised coral islands to avoid the possibility of mistaking recent fringing material for the older nucleus of the island. This difficulty can usually be overcome by taking certain precautions which have been employed by the leaders of the expeditions mentioned below.

It is often noticed that fringing reefs most commonly occur on the leeward side of an island; while on the windward side not only is no fringing reef formed, but the sea makes inroads into the older limestone, forming lines of beach-erosion at various heights. It is also found that in some of the islands examined natural sections or ravines occur, and these often cut through any superficial material, exposing the older rocks. Advantage was taken of these natural features in making the collections, while Mr. E. C. Andrews took the additional precaution of blasting into the solid rock in making his collections from the Fijis.

[1] It would perhaps be better to use the term "negative movement of the shore line."

Collections which have been examined. — The materials for the present inquiry have been obtained by taking selected specimens from the collections of the expeditions about to be described; the specimens have been analyzed chemically with a view to determining to what extent dolomitization occurs in upraised coral islands, and many microscopic sections have been made to illustrate the structural and mineralogical changes which have arisen since the formation of the rocks.

In 1897–98 an expedition was made by Dr. C. W. Andrews, one of the officers of the British Museum (Nat. Hist.) to Christmas Island, in the Indian Ocean. The expenses of this expedition were defrayed by Sir John Murray, and Dr. Andrews remained on the island for about ten months, surveying and making extensive botanical, zoölogical, and geological collections.

On his return to England Dr. Andrews gave a preliminary account of his researches before the Royal Geographical Society.[1]

Since then he has prepared a monograph on the island, and this was published in 1900 by the Trustees of the British Museum.

In 1898 ten selected limestones from the island were placed in my hands for chemical and mineralogical examination, and a short account of the results obtained was incorporated in the published monograph, but it was thought advisable to make a much more extensive examination of the limestones to render more complete our knowledge of the chemical and mineralogical composition of the island. This I have been able to do through the kindness of Professor Judd in obtaining the consent of the Trustees of the British Museum (Nat. Hist.); and I wish here to record my thanks to Dr. Andrews for much help in going over the collection with me and verifying the exact locality of each specimen.

Toward the end of 1897 Mr. Alexander Agassiz, who has had so much experience among coral reefs, commenced a cruise in the "Yaralla" among the islands of the Fiji archipelago. The results of his observations were published in 1899.[2]

At the conclusion of this voyage he organized an expedition to examine in more detail certain of the upraised coral islands of the Fijis, with special reference to the Eastern or Lau group. This expedition was undertaken by Mr. E. C. Andrews, of Sydney University, who made a survey of several of the islands, and collected specimens from the cliffs and terraces. His results were published in November, 1900.[3]

[1] Geographical Journal, January, 1899.
[2] Bull. Mus. Comp. Zoöl., Vol. XXXIII., 1899.
[3] Bull. Mus. Comp. Zoöl., Vol. XXXVIII., 1900.

In 1899–1900 Mr. Agassiz made a further expedition to the Pacific in the "Albatross," visiting the Paumotus, the Tonga or Friendly Islands, and Guam in the Ladrones.[1] Through arrangements made with Professor David and Mr. Agassiz, by Professor Judd, I have been able to examine a small selection of the limestones collected by Mr. E. C. Andrews in the Fijis, and by Mr. Agassiz in the Paumotus, Tongas, Ladrones, etc.

Professor David, on his first expedition from Sydney to Funafuti, visited Niue (Savage Island), and collected limestones from ravine sections and from faces of the raised terraces. These specimens I have examined, and during a recent visit to England Professor David was so kind as to make sketches of the island for me, illustrating the horizons from which the limestones were collected.

Throughout this work I have received from Dr. Cullis, who has had considerable experience with the Funafuti specimens, valuable advice, which I am anxious to acknowledge. I am also indebted to Mr. Frederick Chapman for the specific identification of some of the Foraminifera, while Mr. Franklin T. Barrett and Mr. C. Davies Sherborn have helped me with many valuable suggestions. To Professor Judd my best thanks are due, not only for giving me the opportunity of making this research, but also for valuable help and advice throughout the progress of the investigation.

Historical Introduction. — The very early work of Hatchett[2] dealt with the chemical composition of the skeletons of various organisms, including corals, but his analyses were only qualitative, and his results are only distantly related to the present inquiry. Many years elapsed before another investigator published any results bearing on corals or coral reefs.

The next contribution was from Prof. J. D. Dana — Geologist to the United States Exploring Expedition (Wilkes), 1837–42 — who made an extensive collection of corals and coral rocks from the islands visited during the voyage, including limestones from the raised coral island of "Metia" (Makatea). The specimens were analyzed by Benjamin Silliman, Jun., and Professor Dana made a first reference to the results in an address to the Association of American Geologists and Naturalists, at Albany, in 1843.[3] The work was incomplete, and no analyses were

[1] Mem. Mus. Comp. Zoöl., Vol. XXVI., No. 1, 1902, and Vol. XXVIII. 1903.

[2] Chas. Hatchett, Transactions Royal Society, Vol. XC., 1800, p. 327.

[3] American Journal of Science and Arts, Vol. XLV. 1843, p. 120.

given, but Dana recorded the remarkable fact that in some of the corals and coral rocks Silliman had found a considerable amount of magnesium carbonate.

In the following year (1844), at the Washington meeting of the same Association,[1] Dana again referred to the presence of magnesia in some of the corals, and announced the further discovery by Silliman of a certain amount of calcium phosphate in the specimens analyzed. Silliman's early analyses were faulty, but he corrected them in a later article,[2] and also in the appendix to the report upon the United States Exploring Expedition, "Zoöphytes" (1846), p. 712.

Silliman's analyses included specimens of most of the reef-forming corals. Their hardness and specific gravity led Professor Dana to conclude that the stony corals consisted of aragonite and not of calcite, — a conclusion which was subsequently confirmed by Gustav Rose and Dr. H. C. Sorby.

The general result of Silliman's analyses, showing the limits of variation in the composition of the specimens, was given at the conclusion of his paper, and may be stated as follows: —

Calcium carbonate	90–97	per cent.
Fluorides, phosphates, silicates . . .	$\frac{1}{4}$–$2\frac{1}{2}$	" "
Organic matter	2–8	" "

Silliman's paper did not include his analyses of the coral rocks from the raised island of Makatoa. These were given in Professor Dana's work.[3] The analysis of one specimen was as follows: Calcium carbonate, 61.93 per cent, magnesium carbonate, 38.07 per cent; another gave 5.29 per cent of magnesium carbonate, while the corals themselves contained very little. In the same work Dana quoted analyses of coral sands, and showed that their composition was not different, as regards the magnesia, from that of the corals. The coral sands from the Straits of Balabac gave calcium carbonate, 98.26 per cent, magnesium carbonate, 1.38 per cent, alumina, 0.24 per cent, phosphoric acid and silica, a trace. Professor Dana quoted the analyses from Metia as an instance of dolomitization during the consolidation of the rock beneath sea water, and it was upon the analyses from this island that he based his well-known theory of dolomitization.

In 1847 a paper appeared in the Quarterly Journal of the Geological Society, written by the Rev. W. B. Clarke, on the Geology of the Island

[1] American Journal of Science and Arts, 1844, Vol. XLVII., p. 135.

[2] American Journal of Science and Arts, 1846, 2nd Series, Vol. I., p. 189.

[3] Geology of the United States Exploring Expedition, J. D. Dana, 1849, p. 158.

of Lafû, one of the Loyalty Group, east of New Caledonia, in the South Pacific Ocean.[1] The paper contained no analyses, but consisted mainly of a short description of this raised coral island, some parts of which have been elevated to a height of 250 feet, while a terrace at the level of 80 feet marked a pause during the elevation. The author stated that the corals from the highest part of the island were altered and decomposed, while those near the sea level were quite fresh and unchanged.

In the year 1880 Prof. A. Liversidge[2] published an account of five analyses of some specimens from the South Sea Islands. These included two specimens, — one of a coral from the New Hebrides, the other of a coral limestone from Duke of York Island, both collected *in situ*.

In the analyses the constituents were expressed as oxides, but if the amounts of calcium and magnesium are given as carbonates, they are rendered more comparable with my own analyses, and are approximately as follows: —

Reef-coral, New Hebrides	
Calcium carbonate	97.54
Magnesium carbonate	.17
Sodium chloride	1.02
Silica	.72
Alumina and iron sesqui-oxide	.23
Hygroscopic moisture	.26
	99.94

Coral-rock, Duke of York Island	
Calcium carbonate	98.025
Magnesium carbonate	1.808
Soda	.848
Potash	.983
Silica	.789
Alumina and iron sesqui-oxide	1.973
Organic matter	.500
Hygroscopic moisture	.012
	99.938

Mr. W. O. Crosby has given a very interesting sketch of the elevated coral reefs of Cuba.[3] He noted that the older parts of the island consist of eruptive rocks and slates, that a series of fringing reefs invests the island at various levels up to nearly 2000 feet, and that the highest and oldest reef is no less than 1000 feet thick.

In 1885 Mr. H. B. Guppy read a paper before the Royal Society of Edinburgh[4] on the structure of the Solomon Islands, based on a considerable personal survey of the group. He described the islands as usually having a volcanic peak as a nucleus; over this was found a

1 Q. J. G. S. 1847, Vol. III., p. 61.

2 Royal Society of N. S. W., October 6, 1880.

3 Proceedings of Boston Society of Natural History, 1883, Vol. XXII, pp. 124–130.

4 Transactions Royal Society of Edinburgh, 1885, Vol. XXXII., pp. 545–581.

consolidated volcanic mud derived from the subjacent volcano, and mixed with calcareous organisms such as Foraminifera. This was usually succeeded by foraminiferal limestones composed of calcium carbonate to the extent of 75 to 85 per cent, the remainder consisting of insoluble matter. Raised coral reefs were found by him resting either on the foraminiferal limestones or on the volcanic muds. Although some of the larger islands have been elevated as much as 10,000 feet, Mr. Guppy never found the raised reefs above the level of 600 feet, and they were never more than 150 to 200 feet in thickness.

Most of the analyses, made for Mr. Guppy by Dr. Leonard Dobbin, were of the volcanic muds, but two analyses of coral limestones were added. In one from the Shortland Islands the amount of calcium carbonate was 95.76 per cent; the remainder, 4.24 per cent, consisted of insoluble residue. Another specimen from Choisel Bay gave, on analysis, 94.19 and 5.81 per cent of calcium carbonate and insoluble residue respectively.

In a paper read before the Geological Society, in 1891, Mr. Jukes Brown and Professor Harrison [1] gave a description of the geology of Barbados. They stated that no volcanic rocks occurred, that there was no evidence of subsidence, that six sevenths of the surface of the island were covered with coral rock, having a maximum thickness of 260 feet, and that terraces occurred up to a height of 1100 feet.

The following are the results of nine analyses of some of the raised coral limestones: —

	Calcium Carbonate.	Magnesium Carbonate.	Calcium Phosphate.	Ferric Oxide and Alumina.	Silica and Clay.	Loss on Ignition.	Total.
I.	95.78	2.01	trace	2.27	.05	—	100.11
II.	93.38	2.05	.05	.78	3.10	.70	100.06
III.	96.52	1.74	—	.64	1.20	—	100.10
IV.	99.01	.56	.13	.35	.20	—	100.25
V.	98.09	1.25	.07	.27	.48	—	100.16
VI.	98.80	.87	trace	.19	.29	—	100.15
VII.	97.26	2.44	trace	.17	.13	—	100.00
VIII.	97.50	{ C_aO .41 1.11 }	.21	.05	.91	.26	100.45
IX.	84.89	1.48	.04	2.24	9.48	2.01	100.14

I. Marl near Bennett's, 400 ft.
II. 635 ft.
III. 635 ft. } Plumtree Gully.
IV. 650 ft.
V. Ellis Castle Well, 130 ft. from the surface.
VI. Grove's hard limestone.
VII. Castle Grant limestone.
VIII. Base of coral rock near Codrington.
IX. Crystalline concretionary rock from shaft at Cane Garden.

[1] Q. J. G. S., 1891, pp. 197-246.

At the conclusion of their paper a general statement was given of other localities from which raised coral limestones have been described.

1. *Guadaloupe.* — This island is volcanic on the western side, and has coral reefs on the east, which are found up to a level of 1300 feet.

2. *Antigua.* — Volcanic rocks occur on the west and reefs on the eastern side up to a height of 300 to 400 feet.

3. *Barbuda.* — Coral limestone alone is found, and reaches a height of 117 feet.

4. *Jamaica.* — Raised reefs are never found above 100 feet, but the massive white limestone of the island, which is 2000 feet thick, and covers six sevenths of the surface, contains corals, and probably its upper part is raised reef.

On June 21, 1891, Mr. J. J. Lister read a paper before the Geological Society on the Geology of the Tonga or Friendly Islands.[1] No analyses of limestones were given, but the paper contained an interesting account of the structure of the group, including three islands, Eua, Vavau, and Tongatábu, visited subsequently by Mr. Alexander Agassiz.[2] Mr. Lister distinguished three kinds of islands.

(*a*) Purely volcanic islands.

(*b*) Those having a stratified volcanic base, since elevated, and with or without limestones.

(*c*) Islands entirely of reef origin.

The islands containing limestones were generally found to be characterized by definite terraces at different levels. Mr. Lister concluded that the islands of the Tonga group have probably grown on banks of volcanic origin laid out in shallow water, and that there was no necessity to call in the hypothesis of subsidence to account for their formation.

Dr. G. J. Hinde contributed a short note in 1893 to the Geological Society on specimens of raised limestones from New Hebrides.[3] He quoted no analyses, but microscopically examined limestones from heights of 346, 500, and 1274 feet. They were found to be made up of nullipores (Lithothamnion), corals, and Foraminifera, and there was no evidence of their having had a deep-water origin.

Among those who accompanied the first expedition to Funafuti was Mr. Stanley Gardiner, who has recently published an account of the atoll, and observations on the raised reefs of the Fiji Islands[4] to which Dr.

[1] Q. J. G. S., 1891, pp. 590–616.

[2] Analyses from these islands are given in the body of the present paper.

[3] Q. J. G. S., 1893, pp. 230–231.

[4] Proceedings of the Cambridge Philosophical Society, Vol. IX., pt. viii. p. 417.

Pollard contributed some analyses of limestones from Namuka, Fulanga, and Kambara. These limestones all contained a fair proportion of magnesium carbonate.

Namuka.

White Rock		*Red Rock*	
Calcium carbonate	78.6	Calcium carbonate	85.2
Magnesium carbonate	21.5	Magnesium carbonate	6.7
		Ferric oxide and alumina	4.2
		Silica	3.5
	100.1		99.6

The limestones from Kambara and Fulanga yielded respectively 19.8 and 10.7 per cent of carbonate of magnesium.

References to the earlier expeditions of Mr. Alexander Agassiz among coral reefs are now given in chronological order: —

1878 West Indies. Bull. Mus. Comp. Zoöl., Vol. V., No. 1.

1883 The Tortugas and Florida Reefs. Mem. Am. Acad., Vol. XI., p. 107.

1888 West Indies. Three Cruises of the "Blake," Vol. I., p. 66.

1889 Hawaiian Islands. Bull. Mus. Comp. Zoöl., Vol. XVII., p. 121.

1892 The Galapagos Group. *Ibid.*, Vol. XXIII., No. 1.

1894 Bahamas and Cuba. *Ibid.*, Vol. XXVI., No. 1.

1895 Bermudas. *Ibid.*, Vol. XXVI., No. 2.

1896 Florida. *Ibid.*, Vol. XXVIII., No. 2.

1898 Great Barrier Reef of Australia. *Ibid.*, Vol. XXVIII., No. 4.

1898 Fiji. American Journal of Science, February, 1898, p. 113.

His later expeditions, together with those of Prof. T. W. Edgeworth David, Dr. C. W. Andrews, and Mr. E. C. Andrews have been referred to; but as their collections form the subject-matter for this paper, their published reports will be more particularly noticed in dealing with the microscopical and chemical results obtained from an examination of the collections from the several islands. Mr. R. L. Sherlock has recently examined many of the thin sections, whose microscopical characters are described in this paper, and has identified and named the fossils they contain.[1]

CHEMICAL METHODS. — Before deciding on the quantitative methods to be employed in the chemical examination of the collections, a considerable number of qualitative analyses were made with a view to determin-

[1] Bull. Mus. Comp. Zoöl., 1903, Vol. XXXVIII.

ing all the compounds likely to be present in the rocks, and also to obtain an idea of the proportions of the different constituents. It was found that the most important constituent was calcium carbonate, that many of the rocks contained a considerable amount of magnesium carbonate, and that calcium phosphate was always present, but never in large quantity.

It was also noticed that some of the less altered rocks contained organic matter, that the amount of insoluble residue was as a rule almost inappreciable, and that traces of ferric oxide, alumina, and silica were sometimes found, together with occasional slight reactions for chlorides and sulphates.

These preliminary results serve to show that the calcium and magnesium carbonates constitute practically the whole of the rocks, and this circumstance determined the methods of analysis eventually adopted.

The two methods used were substantially identical with those which have been employed by Dr. Cullis, Mr. Hart-Smith, and myself in the chemical analysis of the Funafuti boring. The details of the gravimetric method may be briefly stated: —

A specimen was prepared for analysis by rejecting the external part which might contain adventitious material. A piece of the more central portion of the limestone, reduced to a powder in an agate mortar and carefully sampled, was washed with boiling water to remove any soluble organic or inorganic matter which might be present, but this amount was found to be negligible. The powder was then dried at 100° C., and for a complete analysis two portions were weighed out.

1. In the first portion the proportions of calcium and magnesium carbonates were estimated. About .8 gram was taken, the calcium precipitated in the ordinary way as oxalate, dissolved and reprecipitated to free from magnesium, and after the careful addition of a few drops of sulphuric acid, heated and weighed as calcium sulphate.

The magnesium was determined from the filtrate by precipitation as phosphate, and was weighed as magnesium pyrophosphate.

2. As insoluble matter and calcium phosphate were present in very small quantity, 10 grams of the limestone were usually taken, dissolved in dilute hydrochloric acid, and filtered through a tared filter paper. The filtrate contained the phosphate, while the insoluble matter, organic and inorganic, remaining on the filter paper, was dried and weighed. By burning off the organic residue, the amount of inorganic insoluble matter was obtained.

The phosphate in the solution was estimated by precipitating with

ammonium molybdate at 40°, dissolving the precipitate in the minimum quantity of ammonia and precipitating as magnesium phosphate by magnesia mixture, and weighing as magnesium pyrophosphate.

Owing to the slight solubility of magnesium phosphate in water, care was taken to keep the bulk of the solution as small as possible.

About fifteen of the specimens from various islands were analyzed gravimetrically as above, but it was felt to be unnecessary to deal with all the limestones — nearly two hundred in number — in the same way, if some volumetric determination could be employed which would be at once more rapid than the gravimetric method, and yet give fairly accurate results.

Such a method has been much used in connection with the Funafuti boring, and was agreed upon by a Chemical Committee of the Royal Society. The details were devised by Professor Tilden, and were first worked out by Mr. J. Hart-Smith, under Dr. Tilden's supervision.

In this volumetric analysis only the calcium is determined. The principle on which the method is based is as follows: —

The addition of a solution of ammonium oxalate to a sufficiently dilute solution containing calcium and magnesium salts, to which a solution of ammonium chloride and ammonia has been added, will precipitate calcium oxalate practically free from magnesium oxalate.

If a known amount of ammonium oxalate is added, — more than is necessary to precipitate all the calcium, — the excess of ammonium oxalate may be determined by titration with potassium permanganate solution. The details of the method may be stated thus: —

Large quantities of the following solutions were made up: —

1. Potassium permanganate, decinormal solution.
2. Ammonium oxalate, one gram in 50 cubic centimeters.
3. Ammonium chloride and ammonia, one gram of each in 25 cubic centimeters.
4. Hydrochloric acid, one gram in 25 cubic centimeters.
5. Sulphuric acid, one gram in 10 cubic centimeters.

About .3 gram of the powdered limestone was dissolved in 25 cubic centimeters of hydrochloric acid solution, and any insoluble residue, if present, was filtered off.

To the solution were now added 150 cubic centimeters of distilled water, and then, from a pipette, 25 cubic centimeters of ammonium chloride and ammonia.

If any appreciable quantity of phosphate were present, a white precipi-

tate was formed, which was filtered off, and the amount of phosphate estimated separately as above.

In most cases no precipitate, or only the slightest turbidity, was noticed, and after the solution was heated, 50 cubic centimeters of the standard solution of ammonium oxalate were run in from a calibrated burette. This precipitated all the calcium as oxalate, and left an excess of oxalate in the solution. The beaker of solution was then cooled to the temperature of the air and poured into a calibrated flask of 250 cubic centimeters' capacity, and filled with distilled water up to the mark in the neck. The solution was next filtered through a dry filter paper, and 100 cubic centimeters of the clear filtrate measured out from a calibrated burette. To this were added 25 cubic centimeters of dilute sulphuric acid; the mixture was then warmed to about 50° C., and titrated with standard permanganate solution from a calibrated burette.

The value of the permanganate had been previously obtained by means of pure ferrous ammonium sulphate and its equivalent in the standard ammonium oxalate solution, determined by titration. With these data the amount of oxalate which had combined with the calcium could be estimated, and from that the percentage of calcium carbonate present in the rock was obtained. When phosphate or insoluble residue was present in determinable quantity, the amounts were ascertained separately by the methods already described, and the percentage quantity added to that of the calcium carbonate. The amount of magnesium carbonate in the rock was then represented by the difference between this figure and one hundred.

This method was used by Mr. Hart-Smith in making determinations of specimens from the Funafuti core. Later, I had the opportunity of making a number of analyses from different depths of the same boring. With both of us the method has yielded consistent and fairly accurate results, and it is this means of analysis which I have mainly employed — confirmed here and there by gravimetric determinations — in working on the limestones from the islands about to be considered. In order to test the method more fully, and with a view to demonstrating to what extent the results yielded by it may be relied on, I made a series of determinations in duplicate, and another series in which gravimetric and volumetric analyses of similar specimens were compared. An examination of the results showed that the maximum difference in 27 determinations of calcium carbonate in duplicate from different limestones was .8 per cent, while the average difference was rather less than .4 per cent. Similarly a comparison of gravimetric and volumetric results of calcium

carbonate from 15 different rocks showed a maximum difference of .93 per cent and an average difference of rather less than .5 per cent.

MICROSCOPICAL METHODS. — In examining the thin sections of the limestones, my attention was directed not so much to the identification of the organisms (these have been described by Mr. R. L. Sherlock[1]) as to the determination of their mineral character, and the changes they and the matrix have undergone. It was as a rule sufficient for my purpose to be able to recognize corals, echinoderms, and molluscan shells, to distinguish between Halimeda and Lithothamnion among the calcareous algæ, and to recognize a few of the more important Foraminifera, such as Polytrema, Amphistegina, Heterostegina, Carpenteria, Orbitolites, Globigerina, etc.

The precise identification of the mineral structure of the organisms, of the crystalline material subsequently deposited on them, and of the general character of the matrix, was not always an easy matter.

In fibrous crystals it was often difficult to distinguish between aragonite and calcite, while occasionally difficulties arose in differentiating calcite from dolomite.

The characters usually relied on for the identification of aragonite are its occurrence in long prismatic crystals, its specific gravity (2.92), and its biaxial character. In contrast with these properties, calcite usually occurs in rhombohedra or scalenohedra, its specific gravity is 2.72, it has a strong rhombohedral cleavage, and it gives a well-marked uniaxial interference figure. Dolomite can, as a rule, be distinguished from calcite[2] by its occurrence in simple unit rhombohedra often showing zoning, its specific gravity (2.9), its higher refraction, and the fact that its cleavage is usually less marked than that of calcite. As a rule, these tests were sufficient for the identification of calcite and dolomite, but gave no certain distinction for aragonite. Organic fragments were often found coated with an encrusting deposit of small radiating crystals, which were too small to allow of a specific gravity determination, while the interference figures given by these minute bundles of crystals were always unsatisfactory. When fibrous crystals were found in optical continuity with the fibers of a coral, there was little doubt that the two substances were identical. In this connection it may be mentioned that a determination of the specific gravity of a coral from Niue, at a height of 80 feet, yielded a result of 2.81.

Where no optical continuity could be traced between the deposited

[1] Bull. Mus. Comp. Zoöl., 1903, Vol. XXXVIII.

[2] Renard, Bull. Acad., Belgique, May, 1879, Vol. XLVII., No. 5.

crystals and the coral fibers, some other critical test was desirable in order to distinguish between calcite and aragonite.

Such a method has been described recently by W. Meigen.[1]

The method consists in boiling the powdered substance for a few minutes in a solution of commercial cobalt nitrate, when a lilac-red precipitate of basic carbonate of cobalt indicates the presence of aragonite, while calcite remains unaffected, or in the presence of organic matter becomes yellowish. Barium and strontium, but not magnesium carbonates, give the same result as aragonite, while calcium phosphate produces a blue precipitate.

By means of this reaction Meigen distinguished aragonite from calcite in various animal and vegetable secretions of calcium carbonate.

A few of the results of his determinations are here enumerated:

Aragonite Organisms: —

CALCAREOUS ALGÆ — Halimeda.

CORALS — Heliopora, Montipora, Madrepora, Millepora, Goniastrea, Podobacia, Galaxea, Fungia, Porites, etc.

LAMELLIBRANCHS — Pholas, Cardium, Lucina, Mya, Cytheraea Unio (inner layer of shell), Trigonia (inner layer of shell).

GASTROPODS — Helix, Pupa, Bulimus, Cyclostoma, Natica.

CEPHALOPODS — Nautilus, Spirula, Sepia.

Calcite Organisms: —

CALCAREOUS ALGÆ — Lithophyllum, Lithothamnion.

CORALS — Isis, Tubipora, Cystiphyllum, Anabacia.

FORAMINIFERA — Polytrema, Nummulites.

WORMS — Serpula.

ECHINODERMS.

Meigen's method was tested by me in the following way, and found to give satisfactory results: —

First, the pure minerals, calcite and aragonite, were treated separately, both powdered and in crystals. In each case the calcite was quite unaffected after long boiling, while the pink stain on the aragonite was deeper in the powder than on a crystal surface. A coral sand containing gastropods, echinid spines, and Foraminifera was next treated, and it was found that the gastropods stained deeply, but the echinid spines and Foraminifera were unaffected. A polished slice of a limestone was taken and boiled for half an hour with cobalt nitrate solution. The limestone consisted of coral fragments, gastropods, echinid spines,

[1] Centralblatt für Mineralogie, 1901, pp. 577–578.

Halimeda, etc., cemented with a large quantity of fibrous calcium carbonate. After treatment with cobalt nitrate the slice was mounted, polished surface downward, on a glass slip, and the slice ground down till it was quite transparent. A cover-glass was then mounted on the section, and it was found that the corals, gastropods, and Halimeda were all stained red, the solid walls of the coral being less deeply stained than the septa. The echinid spine was quite unaltered, and no sign of staining was seen on the stalagmitic fibrous calcium carbonate forming the cementing ground mass of the rock. This cement is thus shown to consist of *fibrous crystals of calcite.* It remained to test the prismatic crystals which were occasionally found in optical continuity with coral fibers. A slide showing this was prepared as above described, and it was then found that the septa of the coral and the "dark line" were stained a deep red, the solid parts of the coral and the prismatic crystals in continuity with the coral fibers were colored a lighter pink, while some clear crystalline calcite which filled other cavities was entirely unaffected. The *prismatic crystals in continuity with coral fibers* were thus shown to be *aragonite.*

In discriminating between calcite and dolomite, there was, as a rule, not so much difficulty. The more idiomorphic character of dolomite crystals and their frequent zoning usually served to distinguish them, and when the two minerals occurred associated together, the higher refractive index of dolomite gave it a relief which was a useful diagnostic character. In cases of doubt Lemberg's[1] test was applied, with satisfactory results.

The test consists in applying to the exposed surface of a thin section for about 5 to 15 minutes a solution containing a mixture of aluminium chloride and haematoxylin. Under these circumstances dolomite and brucite are unchanged, but a deposit of aluminium hydrate forms on the less stable calcite, and is stained a reddish purple by the haematoxylin.

The staining solution is prepared by dissolving four parts of dry aluminium chloride in 60 parts of water, and adding six parts of logwood (Haematoxylin campechianum). The whole was boiled and stirred for 25 minutes, and made up to the same bulk after filtration. It is not advisable to allow the staining solution to remain on the rock for more than 15 minutes, as dolomite is slowly acted upon, and also a thicker layer of alumina is deposited on the calcite, which is more easily peeled off and shrinks more on drying. After being stained, the section is

[1] Zeitschrift der deutschen geologischen Gesellschaft, 1888, Vol. XL., p. 357.

dried, Canada balsam, somewhat diluted with ether, is poured upon it, and the cover-glass adjusted.

The works of Gustav Rose [1] and of Dr. H. C. Sorby [2] have dealt largely with the mineralogical constitution of various organisms, and to these papers, especially that of Dr. Sorby, I am indebted for many helpful suggestions.

One of the results of their researches went to show that the mineral composition of most of the reef-forming corals is aragonite. This view remained practically unquestioned till 1900, when Miss Agnes Kelly's paper [3] appeared "On a new form of calcium carbonate," to which she gave the name of conchite. The skeletons of the organisms which have hitherto been described as being aragonite are claimed by Miss Kelly to consist in reality of conchite. It is said to differ from aragonite in its uniaxial character and the lower temperature at which it passes over into calcite and to have a refractive index intermediate between those of calcite and aragonite.

Quite recently, however, Reinhard Brauns,[4] in a paper on the relation of conchite to aragonite, states that while there appear to be certain differences, at present there is not positive evidence sufficient to warrant the making of a new mineral species.

Another paper on ktypeite and conchite, by Henrich Vater,[5] has recently appeared, in which he agrees with R. Brauns in saying that conchite is probably identical with aragonite.

As the question is still in doubt, I have used only the term aragonite for all material which stains with cobalt nitrate, but if Miss Kelly should eventually be proved to be correct in her contention, those crystals which are in optical continuity with coral fibers would have to be known as conchite.

The details of the chemical and microscopical analyses from each island will now be given. It is to be noted that gravimetric analyses are recorded to two places of decimals, while the results of volumetric determinations are given only to the first decimal place.

A certain number only of the limestones have been sliced, and the details of their structure and composition are given below. In the descriptions of the thin sections under the microscope the term "mud" is

[1] Abh. K. Akad. d. Wiss. in Berlin, 1858.
[2] Pres. Address to Geol. Soc., 1879.
[3] Bav. Academy, May, 1900, and Min. Mag., June, 1900.
[4] Centralblatt für Mineralogie, 1901, pp. 134–135.
[5] Zeitschrift für Krystallographie und Mineralogie, 1901, Vol. XXXV., p. 149.

frequently employed to express the appearance of the finest calcareous detrital material and is not intended to convey the idea of an argillaceous sediment. In this part of the work I have endeavored to record the facts so far as I have been able to observe them, leaving any theoretical bearing these may have to be dealt with at the conclusion of the paper.

II. Chemical and Microscopical Results.

1. Pacific Ocean.

A. The Fiji Group (Eastern or Lau Division).

Mango. — Mango is an island subcircular in shape, and about 3½ miles in diameter, situated in latitude 17° 25′ S. and longitude 179° 10′ W. Mr. E. C. Andrews's published descriptions,[1] with maps and sections, give a good idea of the general structure of the island. It consists of an elevated ring of limestone, with bold cliffs often over 400 feet in height. Patches of recently raised reefs occur here and there on the lower slopes, while along the inland cliffs old reefs are met with at levels of 50 and 250 feet, and traces of a terrace occur up to 200 feet in the cliffs on the northern and southern limits of the island. The ring of elevated limestone is now not continuous all round the island, but has been broken through at the north-western and south-eastern margins by very extensive andesitic flows proceeding from two volcanic centers, one in the south-east of the island, the other north-west of its center. The limestone is still further obscured over the central depression by the formation of a considerable deposit of volcanic alluvium. On the north-east of the island there is a small lagoon, connected by a narrow channel with the sea. This depression probably represents a former means of communication between the outer sea and the central lagoon. The limestones which I have examined were collected by Mr. E. C. Andrews from among the older unbedded limestones of the sea-cliffs at definite heights above high-water mark. They are all younger than the basal limestones which are exposed here and there. These basal limestones dip at 15°–20°, and are interbedded with "soapstone."

Chemical. — Most of the rocks consist of highly dolomitic limestones; but at a few points, notably, at 370, 310, and 298 feet, limestones occur with only 4.9, 9.7, and 10.7 per cent of magnesium carbonate respec-

[1] Bull. Mus. Comp. Zoöl., 1900, Vol. XXXVIII., pp. 17-20.

tively. At a height of 280 feet a rock is found in which magnesium carbonate is represented to the extent of 27.3 per cent. An interesting point is that most of the analyses yield from 38 to 42 per cent of magnesium carbonate, but none of them approach nearer to the composition of a true dolomite. Calcium phosphate is found in most of the rocks, but usually only in traces, as .29 per cent was the maximum amount obtained.

Insoluble residue is present in exceedingly small quantities, except where the limestones are associated with volcanic rocks. This association will explain the unusually high value of 4.03 per cent obtained from the limestone at 420 feet. The adjoined tabular statement gives the details of the analyses, and the accompanying diagram represents the proportion of calcium to magnesium carbonate, expressed graphically in the case of three rocks which occur in vertical succession in one cliff face. The shaded area represents the percentage of magnesium carbonate, the unshaded area representing calcium carbonate. The dotted line is drawn at a point representing 46 per cent of magnesium carbonate, the proportion represented in a true dolomite. The curve is obtained by joining all points at which specimens were collected in vertical succession from a cliff face. The remaining specimens were collected at the stated heights from isolated spots in various parts of the island, but are interesting as showing the occurrence of dolomitic and non-dolomitic limestones at different heights in the island.

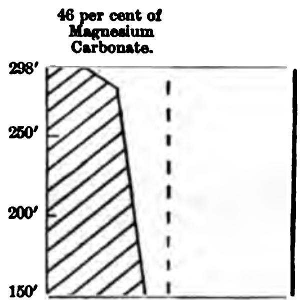
These diagrams, therefore, do not represent completely the chemical composition of all the rocks between the highest and lowest specimens, but are used as a convenient means of presenting at a glance the detailed results of the analyses at stated heights.

Microscopical. 510′. — A thoroughly dolomitized rock in which the organisms are nearly obliterated. Some of the cavities are lined by a deposit resembling agate. It consists of 6 layers of sharply defined crystals alternately dolomite and calcite, as shown by staining; the central layer filling the remainder of each cavity consists of broad platy crystals of calcite. Some of the dolomite rhombohedra have dark opaque irregular centers, which by staining with Lemberg's solution are proved to consist of calcite.

400′. — A fine-grained dolomitic limestone, in which organisms such as Lithothamnion and Carpenteria are found, only slightly altered, while others, such as Amphistegina (?) are quite removed, and their former presence can only be suggested by the similarity of the shape of the cavities to the external boundary of the organisms. Many casts of coral occur, in which the septa are represented by a gray "silt" lined with

Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.	Calcium Phosphate.
510′	59.4	40.6	—	—
435′	59.29	40.70	—	—
420′	84.2	11.8	4.03	—
410′	62.7	37.3	—	—
400′	60.66	38.50	—	—
380′	62.9	37.1	—	—
370′	94.9	4.9	.16	—
350′	69.5	30.2	.34	—
335′	59.5	40.5	—	—
330′	58.7	41.3	—	—
320′	58.3	41.7	—	—
310′	90.16	9.70	.10	.29
300′	61.2	38.8	—	—
298′	88.0	10.7	1.26	—
290′	59.5	40.5	—	—
280′	72.3	27.3	—	—
250′	66.0	34.0	—	—
200′	61.2	38.8	—	—
195′	97.2	2.8	—	—
155′	61.7	38.3	—	—
150′	62.3	37.3	—	—
145′	78.6	21.4	1.43	—
105′	63.6	36.4	—	—
73′	75.4	24.6	—	—
40′	60.1	39.9	—	—
20′	57.7	42.3	—	—
6′	60.8	39.2	—	—

MANGO.



clear dolomite. The matrix consists entirely of silt, having a semi-transparent appearance, due to its consisting largely of minute rhombohedra of dolomite. The obliteration or solution of some of the corals and Foraminifera renders the rock somewhat cavernous.

370′. Figure IV. A "coral sand" or limestone, made up of small fragments of Carpenteria, Gypsina, Lithothamnion, and echinid spines. Some organic fragments are entirely recrystallized in clear calcite, the former boundary of the organism being marked by a "dirt line," while the stereoplasm of the corals has been replaced by calcite, and the spaces between the septa filled with "mud." The matrix consists partly of mud and partly of its alteration product calcite.

350′. Interest in this slide centers in the fact that the dolomite rhombohedra consist of three parts, a central rhomb of dolomite, a middle layer of calcite, and an outer one of dolomite. All three layers have quite sharp rhombohedral angles and all are in optical continuity.

335′. The whole of the matrix is dolomitized, as are all the organisms except the central parts of the Lithothamnion. Clear crystals encrusting the fragments of some of the organisms have an outer layer of slightly higher refractive index. This outer layer does not stain, while the central crystal which is slightly rounded, after treatment with Lemberg's solution for half an hour is colored a light pink. This, in conjunction with the evidence of refractive index, seems to suggest that the central layer may be calcite, containing some magnesium, while the peripheral part consists of a purer dolomite.

320′. Figure X. Reference to the figure shows that this slide consists of a longitudinal section of a coral, in which the organism has been converted into dolomite without the complete destruction of its structure. This is shown by the fact that the original borings made in the coral by algæ, and subsequently filled with "mud," still remain in the same position in the coral, with the mud apparently unaltered. Dirt lines mark the original extent of the walls of the septa, and these are now incrusted with clear dolomite crystals. Many cavities are filled with "mud" up to a certain level, and the surfaces of these "dirt floors" are roughly parallel to one another. Other cavities have been filled with large, slightly yellow plates of calcite. Lithothamnion occurs apparently unaltered, but under the high power its tubules are seen to be filled with small dolomite crystals.

310′. This limestone is interesting on account of the occurrence in it of many examples of the foraminifer Orbitoides. Mr. Frederick Chapman has kindly identified it for me as the form *Orbitoides sumatrensis*, a form

which occurs in some of the upper limestones of Christmas Island, and to which a Miocene age has been assigned.

Polytrema and Lithothamnion also occur in this rock, which has a matrix consisting largely of "mud," while some of the cavities are lined with scalenohedral crystals of calcite.

300′. A fragmental rock, which, by the thorough dolomitization of matrix and organisms alike, has become clear and crystalline. Lithothamnion partly resists change, and one simple coral is represented by a cast in "mud." No other forms are recognizable; even the "dirt lines" round the boundaries of formerly existing organisms have been recrystallized. Cavities and cracks in the rock are more or less filled with large plates of secondary calcite.

298′. This limestone was probably a beach deposit. It consists of rounded fragments of limestone and dolomite, with other fragments of volcanic origin, probably basalt. These rounded grains are seen to touch one another in places, and are invested with a concentric coating of fibrous calcite, while the remaining space is filled with a mosaic of calcite crystals.

290′. Figure IX. A thoroughly dolomitic cavernous rock, with Lithothamnion and meandrine structures, probably "ghosts" of corals. Secondary calcite fills many of the cavities.

280′. A dolomitic limestone, largely composed of Lithothamnion and Carpenteria. The former is usually unaltered, but the latter has recrystallized in large crystals of clear calcite, and would be difficult to recognize but for the numerous tubules running into the calcite. These tubules have been filled with a "mud," which in places can be seen to have altered to little rhombs of dolomite.

250′. A dolomitic limestone in which meandrine forms, possibly corals, are the only remaining organisms, while many cavities are filled with secondary calcite.

195′. A comparatively fresh limestone with a fine-grained cement of calcite. Carpenteria and Polytrema are the most abundant organisms, but Lithothamnion and echinid spines are also noticed.

105′. A rock in which all the matrix and most of the organisms have been dolomitized. Some specimens of Lithothamnion, however, show that the invasion of dolomite has been only partially effected, as the central parts are still calcite. Meandrine fragments of other organisms also remain as calcite, and a secondary deposit of this mineral fills some of the larger cavities in the rock. Many of the dolomite crystals, especially those formed round the meandrine organisms, have centers of

calcite. These centers are sometimes crystalline and rhombohedral in shape, but often consist of irregular inclusions of muddy calcite.

20′. A cavernous dolomite whose appearance suggests that most of the organisms originally present in the rock have been subsequently dissolved. Lithothamnion is still recognizable, although completely dolomitized.

6′ A. A longitudinal section of a dolomitized coral is seen, showing many mud-floors and tubes of algæ. Many of the dolomite rhombs have an outer layer of calcite optically continuous with the dolomite. The larger cavities in the coral have been subsequently filled with broad crystals of calcite.

6′ B. Chiefly consists of a dolomitic cement with sections of Lithothamnion and echinid spines, which, though dolomitized, still preserve their structures. Cavities are lined with a deposit consisting of four successive layers alternately dolomite and calcite, the last layer forming broad calcite crystals completely filling the remainders of the cavities.

6′ C. This dolomitic limestone contains few recognizable organisms. Meandrine forms occur in a dolomitic "mud"; Amphistegina and Orbitolites are very much altered, or represented only by casts, while all stages in the disintegration of Lithothamnion can be seen in this section, the gradual invasion of the organism by dolomite taking place from without inwards, so that in some fragments the outer margin of the organism is obliterated, while the central part appears quite unaltered.

NGILLANGILLAH. — Ngillangillah is a small island near Vanua Mbalavu, in the Exploring Isles, in latitude 17° 10′ S., longitude 179° 2′ W. It is entirely composed of elevated limestone, and reaches a height of 510 feet.[1]

The island appears to consist of masses of coral reef or reef débris, with a bedded limestone underlying the coral rock, not exposed in this island, but seen in Bai Vatu, a few miles to the south. There are traces of three or four separate upheavals visible on the island.[2]

The limestones examined were collected in vertical sequence from one of the cliff faces. Mr. E. C. Andrews is of the opinion that the specimens collected near the sea level belong to younger fringing reefs formed at a late stage of the movement of elevation.

Chemical. — An inspection of the tabulated analyses or the appended diagram will show that the composition of the island from top to bottom is remarkably uniform. All the limestones are dolomitized, and the

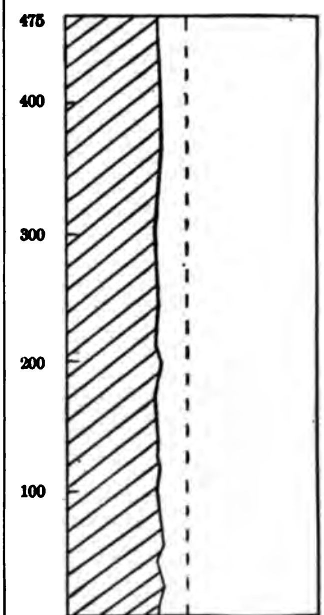
[1] Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII., p. 90.

[2] Bull. Mus. Comp. Zoöl., 1900, Vol. XXXVIII., pp. 28 and 31.

limits of variation in the amount of magnesium carbonate are very small, the minimum value being 34.6 and the maximum 39.1 per cent. Insoluble residue and calcium phosphate are present only in very minute quantities.

Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.	Calcium Phosphate.
475′	65.4	34.6	.02	—
405′	63.4	36.6	—	—
365′	63.0	37.0	—	—
305′	64.6	35.4	—	—
250′	63.7	36.3	—	—
215′	64.2	35.8	—	—
200′	62.0	38.0	—	—
175′	67.6	34.9	0.1	—
140′	62.78	36.68	—	.064
127′	63.4	36.6	—	—
120′	62.1	37.9	—	—
100′	63.4	36.6	—	—
90′	63.5	36.5	—	—
55′	61.6	38.3	.07	—
45′	63.6	36.4	—	—
25′	60.9	39.1	—	—
6′	63.3	36.7	—	—

NGILLANGILLAH.



Microscopical. 475′.—The appearance of the section suggests that the rock was a fragmental limestone made up of Lithothamnion and other organisms, largely cemented by an incrusting deposit of radiating crystals of calcite. Subsequently the rock has been dolomitized. In some parts of the rock the matrix was originally "mud," some of which has since altered to more or less clear granular dolomite.

215′. A dolomitic limestone, in which the only recognizable organisms are Amphistegina, altered Lithothamnion, and "ghosts" of corals, now represented by infillings of "mud" between the septa of the vanished

corals. The rest of the section consists of clear dolomite, much of which is zoned.

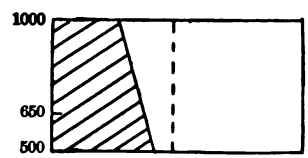
25′. The slide is cut to show a transverse section of a dolomitized coral — Figure VIII. — in which the inner and outer walls of the coral can be traced by "dirt lines." Many of the cavities between the septa are empty, except for a lining of dolomite crystals on the walls, but some are filled with a dark "mud" containing fragments of organisms. This "mud" filled the cavities in which it occurs before dolomitization took place. This is proved by its being in contact with the wall of the coral, and by the layer of dolomite crystals incrusting the "mud" and not the coral wall. Staining with Lemberg's solution shows that in this case the "mud" probably remains as calcite, though in some other rocks it appears to become dolomitized without apparent change. Quite distinct from this dark "mud" is a gray "silt," which is found in the place of the stereoplasm of the coral. This material must have been formed after the dark "mud" was deposited, and after, or as a result of the breaking down of the stereoplasm of the coral. It sometimes occurs in corals preserved in calcite when its composition must be similar, sometimes as in this case there is little doubt that it is dolomitic, as dolomite crystals are seen to have formed within it, and never in the dark "mud" filling the interseptal spaces.

VATU VARA. — Vatu Vara or Hat Island is in latitude 17° 20′ S., longitude 179° 30′ W.[1]

The island is one mile and a quarter in diameter, its summit is flat (consisting of a small reef), and falls off on each side in steep cliffs. It attains an altitude of 1030 feet, and from top to bottom is composed of limestone. Traces of five uplifts are visible on its ascent; three of these are "terrace" formations, while two are represented by beach erosion lines.

Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
1000′	74.3	25.5	.20
650′	60.7	39.3	—
500′	58.45	41.47	—

VATU VARA.



Chemical. — Only three specimens have reached me, and they are all dolomitic. The percentage of magnesium carbonate increases from 25.5 at 1000 feet to 39.3 at 650 feet, while at 500 feet it reaches 41.47.

[1] Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII.

Microscopical. 1000′. — A fine-grained cavernous dolomite, whose cavities have been filled subsequently with clear secondary calcite, reducing the proportion of magnesium carbonate to 25.5 per cent. The organisms present are Lithothamnion, and possibly Polytrema, while meandrine strings of dolomite crystals, filled in with secondary calcite, suggest the former presence of corals.

650′. A very porcellanous-looking fine-grained dolomite, whose cavities and cracks are filled with secondary calcite. No organisms are recognizable.

500′. A fine-grained silty dolomite, whose organic contents, very much altered, consist of decomposed Lithothamnion and casts of Orbitolites. Cavities in the rock are lined with clearer crystals of dolomite.

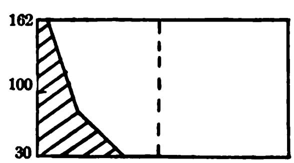
NAMUKA. — This island is 4½ miles long, and consists of a narrow undulating ridge, rising in places to a height of 240 feet.[1]

It is formed wholly of elevated limestone, and is situated in latitude 18° 50′ S., longitude 178° 35′ W. It forms one of the most southerly islands of the Eastern or Lau group of the Fiji Archipelago.

Chemical. — Only three limestones were available for analysis, of which two were found to be dolomitic. The uppermost specimen, from a height of 162 feet, is a limestone containing only 2.5 per cent of magnesium carbonate, but has .78 per cent of insoluble residue, a high value for a coral limestone unassociated with rocks of other than coral origin. At a height of 75 feet the magnesium carbonate has increased to 17.7 per cent, while no less than 34.5 per cent is found in the lowest rock from a height of 30 feet.

Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
162′	96.7	2.5	.78
75′	82.3	17.7	—
80′	65.5	84.5	—

NAMUKA.



Microscopical. 162′. — A fine-grained consolidated "mud," formerly full of organic fragments, a few of which remain (Lithothamnion), but nearly all have been replaced by calcite pseudomorphs. The rock is much cracked, the sides of the cracks being lined first with an iron staining and then completely filled from solution by crystals of calcite, projecting

[1] Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII., p. 57.

from the walls of the cracks and meeting in the center in a notched line, suggesting the "comb" structure in a mineral vein.

75′. The rock contains meandrine organisms (probably "ghosts" of corals), altered Lithothamnion, Foraminifera, and echinid spines. All the organisms, with the exception of the echinid spines, are much dolomitized, and in many cases crystals of dolomite are incrusting the organisms. Between the organic fragments granular calcite occurs in large amount. The limestone was probably originally a fragmental rock, becoming subsequently highly dolomitized. After dolomitization the many spaces in the cavernous dolomite were filled with a clear mosaic of calcite. The echinid spines which had resisted dolomitization have received a secondary deposit of calcite round them in optical continuity with the original organisms.

30′. A similar rock to the last one described, but with the difference that the proportion of dolomitized organisms to secondary calcite is much larger. A good deal of "mud" also occurs as a matrix to some of the organisms. Particular interest centers in one of the organisms, a rather altered Orbitoides which could not be specifically identified. It goes to show, however, that the rock in which it occurs is not later than Miocene in age.

YATHATA. — Yathata is one of the northern islands of the Lau group,[1] and is situated in latitude 17° 15′ S., longitude 179° 30′ W. It rises to a height of 840 feet, and six well-marked terraces occur on its slopes. On the western side of the island a volcanic mass reaches the 500 feet level, scorching and whitening the limestone.

Chemical. — The only specimen available was from near the summit of the island at a height of 800 feet. It consists of a highly dolomitic limestone, with 38.7 per cent. of magnesium carbonate.

Height.	Calcium Carbonate.	Magnesium Carbonate.
800′	61.3	38.7

Microscopical. — Among the organisms which formerly were present in large numbers, only Lithothamnion and Polytrema retain their structure. The remainder are represented by dirt outlines, filled in with clear dolomite crystals. The matrix of the rock is a gray, partly crystalline "mud."

KAMBARA. — Kambara occurs at the southern end of the Lau group in latitude 18° 57′ S., longitude 178° 55′ W. Its structure[2] is very

[1] Bull. Mus. Comp. Zoöl., 1900, Vol. XXXVIII., p. 22.
[2] Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII., p. 98.

similar to that of Mango. It consists of a rim of elevated limestone, rising to a height of 300 to 350 feet, with a central depression. The island is elliptical in shape, nearly five miles long, with a greatest breadth of three miles. On the north-west face the limestone is broken through by a conical hill 470 feet high, which is of volcanic origin.

Chemical. — The only limestone examined came from a height of 250 feet, and contains 34.5 per cent of magnesium carbonate.

Height.	Calcium Carbonate.	Magnesium Carbonate.
250′	65.5	34.5

Microscropical. 250′. — The matrix of the rock consists largely of a fine gray "mud," which under the high power is in places seen to consist of minute crystals of dolomite. Apparently the organisms have not shared in the dolomitization as, for the most part, they seem to be fresh and unaltered. Carpenteria shows its brown color, Lithothamnion, alcyonarian spicules, and echinid spines are apparently unaltered, while Heterostegina preserves its structure except for small wedge-shaped parts of the shell, which were probably aragonite and have now disappeared.

SINGATOKA (Viti Levu). — This district is on the south-western border of the island of Viti Levu, the largest of the Fiji Archipelago.[1] The locality from which the specimens were collected is at the mouth of the Singatoka River, in latitude 18° 10′ S., longitude 177° 30′ E., where large deposits of upraised bedded limestone, dipping at 15°, form cliffs of 250–300 feet in height. Beneath these limestones a compact blue limestone is found dipping at 50°, while below this occurs an immense block of dolomite, practically perpendicular, and consisting of two hills, 1000 and 1500 feet respectively above the river.

Chemical. — The four specimens analyzed were taken in vertical succession from the upraised bedded limestones, which have a dip of 15°. All the rocks are limestones containing only from 3 to 6 per cent of magnesium carbonate. They are interesting chiefly on account of the relatively large quantity of insoluble matter which they contain. The rock from the reef has a smaller quantity, about 1 per cent, but the three specimens from the cliffs yielded on analysis 1.9, 2.09, and 2.31 per cent respectively of insoluble matter.

[1] Bull. Mus. Comp. Zoöl., 1900, Vol. XXXVIII., pp. 13–14.

Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
268′	92.1	6.0	1.90
251′	94.4	4.8	2.31
248′	93.3	4.6	2.09
Reef	95.3	3.6	1.06

Microscopical. 268′. — A foraminiferal consolidated "mud," in which Amphistegina is common. Insoluble material can be recognized in the section.

251′. A cavernous, crystalline rock, containing Gypsina, Carpenteria, and rotaline forms of Foraminifera.

Reef. — A very crumbling rock, made up of fragments of Lithothamnion, Carpenteria, and Amphistegina in a matrix consisting partly of "mud," but mainly of crystalline calcite.

B. Niue.

Niue or Savage Island is a small mass entirely composed of raised coral limestone, situated in latitude 19° 10′ S., longitude 169° 47′ W., about 350 miles east of the Tonga or Friendly Islands. Besides the living reef there are three well-marked raised reefs or terraces at 80, 120, and 200 feet respectively. The highest point of the island is a little over 200 feet, and there is a well-marked central depression or lagoon. I am indebted to Professor David for a description and sketch of the structure of the island. At one part a natural ravine occurs, cutting through the first raised reef into a mass of coral rubble, dipping at 40° and forming the basis on which the second raised reef rests. Professor David, besides collecting specimens from the first, second, and third raised reefs, obtained specimens at intervals of five or six feet up to 70 feet from the ravine of rubble rock.

Chemical. — All the rocks are limestones, with a small quantity of magnesium carbonate, varying in amount from 3 to 8.8 per cent. Gravimetric analysis of a specimen of rubble rock at 53 feet shows that nearly 1½ per cent of soluble organic matter is present, and since all the rocks are comparatively unaltered, it is probable that some organic matter is present in all the specimens. Since the magnesium carbonate is estimated by difference, this will have the effect of making the results for that compound slightly too high. Insoluble inorganic matter is present only in minute quantities, and the same remark holds good of the amount of calcium phosphate present in the rocks.

Microscopical. 80′. *First Terrace.* — A transverse section of a large compound reef-forming coral (Figure 1.). The coral is very fresh, show-

ing the "centers of calcification" and spicular structure. Most of the cavities are empty, but some are filled with a dark "mud," while in others long prismatic, rather muddy crystals of aragonite have arisen by alteration of the "mud." These crystals of aragonite are seen to be crystallographically continuous with the spicules, making up the stereoplasm of the coral.

Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.	Calcium Phosphate.
200′	94.2	5.8	—	—
190′	97.0	3.0	—	—
120′	95.0	5.0	—	—
120′	96.7	3.3	—	—
120′	92.8	7.2	—	—
70′	96.9	3.1	—	—
70′	91.2	8.8	—	—
65′	96.5	3.5	—	—
59′	95.3	4.7	—	—
58′	91.15	6.72	Organic 1.83	.22
47′	96.0	4.0	—	—
42′	96.7	3.3	—	—
36′	95.1	4.9	—	—
30′	96.8	3.2	—	—
24′	96.6	3.4	—	—
18′	96.7	3.3	—	—
12′	96.1	3.9	—	—
6′	96.2	3.7	.18	—

120′. *Second Terrace.* — A rock made up of rounded or angular fragments of coral, Halimeda, Orbitolites, etc. The matrix consists partly of "mud," but very largely of a deposit of radiating fibrous crystals of calcite, forming a concentric coating to the organic fragments. Any spaces left in the rock have been subsequently filled with a mosaic of calcite crystals.

200′. *Third Terrace.* — Section of a reef-forming coral (Figure 2) showing the spicular structure of the coral, the centers of calcification, and the thin mud-filled tubes of boring algæ, which here and there have penetrated the substance of the coral. One cavity in the coral is filled with "mud" containing small organic fragments, while another is seen to have entirely recrystallized. Lining the walls of the cavity the spicular character of the coral seems to have determined that prismatic crystals of aragonite should be formed in crystallographic continuity with the coral fibers. The remainder of the cavity is filled with a mosaic of calcite crystals except round the tubes of algæ, where long prismatic crystals, probably aragonite, have been formed.

70′. Section of rubble below Second Terrace. One half of the section represents a rock made of organic fragments, coated with a deposit of fibrous calcite, cemented together with a mosaic of calcite. This rock was planed down, and on the planed surface a layer of incrusting Polytrema grew, which has since recrystallized to clear calcite crystals. Above this the rock consists of a "mud," into which project from the surface of the Polytrema very large triangular-shaped crystals of calcite. The organisms include a radiolarian, two tunicate spicules enclosed by *Polytrema planum* and several perfect sections of Tinoporus.

65′. Section of a reef-forming coral, some of whose cavities are empty, some filled with "mud" altering to aragonite, some with aragonite optically continuous with the coral fibers, while others are filled with a mosaic of calcite crystals. The difference between aragonite and calcite is well seen after boiling with cobalt nitrate.

53′. A certain amount of incrusting fibrous calcite occurs, investing organic fragments. In some coral fragments aragonite has been formed, but most of the matrix and the material filling the cracks is calcite. The organisms include Halimeda, Lithothamnion, coral fragments and alcyonarian spicules, and a number of small rounded mud pellets suggest in appearance the excrement of fish.

18′. The matrix of the rock is chiefly "mud," but some has crystallized in the form of calcite. Aragonite organisms, such as Halimeda and corals, remain unaltered, and secondary aragonite partly fills some cavities in the coral.

15′. Largely made up of coral fragments with some Carpenteria, tunicate spicules and echinid spines. It was originally cemented by an investing layer of concentric fibrous calcite. Subsequent extensive solution has removed most of this layer and has in places dissolved part of the organisms.

C. The Tonga Group.

The Tonga, or Friendly Islands, consist of an elliptical ring of islands, of which the most important members are Eua, Tongatábu, and Vavau.

EUA. — The most southerly island of the Tonga Group is Eua, which is situated in latitude 21° 20′ S., longitude 174° 55′ W. The island rests on a volcanic base,[1] and consists largely of elevated limestone with vertical cliffs on the eastern face, some of which are over 1000 feet in height. At all projecting parts are lines of terraces; at the north three are visible, at the south five, and traces of a sixth. The island is composed of two ridges[2] running north and south, and separated by a deep valley. The western ridge is 500 feet in height, the eastern one 1000 feet or more.

Chemical. — A specimen collected from the slopes of the central valley at 600 feet contained 7.7 per cent of magnesium carbonate, while another from the second terrace at 250 feet yielded only 4.5 per cent. The third specimen was from the first terrace at 120 feet, and was found to be highly dolomitic, containing no less than 40.4 per cent of magnesium carbonate.

Height.	Calcium Carbonate.	Magnesium Carbonate.
600′	92.3	7.7
250′	95.5	4.5
120′	59.6	40.4

Microscopical. 600′. — A crystallized "coral sand" and "mud" from the central valley of the island. One coral present shows its original structure, but the rest are represented by "ghosts," consisting of a dirt line surrounding clear calcite. The matrix is partly "mud," partly granular calcite.

250′. *Second Terrace.* — Fragments of Globigerina, Carpenteria, Halimeda, etc., are set in dark "mud." The aragonite organisms such as Halimeda are recrystallized, as are some of the calcite forms such as Globigerina. Carpenteria, however, retains its fresh brown appearance.

120′. *First Terrace.* — This appears to have been a coral "mud" which has been dolomitized. Some of the organisms such as Carpenteria and alcyonarian spicules remain apparently unaltered. The arrangement of the crystals round some cavities suggests deposition from solution.

[1] Notes on the Geology of the Tonga Islands, J. J. Lister, Q. J. G. S., Vol. XLVII., pp. 590–616.

[2] American Journal of Science, 1900, p. 193; Mem. Mus. Comp. Zoöl., 1902, XXVI., No. 1, p. 87.

TONGATÁBU. — Tongatábu is an irregular crescent-shaped island 22 miles long, situated in latitude 21° 10′ S., longitude 175° 10′ W.[1] The cliffs on the south coast rise to a height of 250 feet, and then fall towards the north coast to 10 or 20 feet. Round the coast three terraces are seen, and the interior is partly occupied by a shallow lagoon.

Chemical. — The only limestone examined was from Mount Sion Hill, at a height of 50 feet, and contained only 2.3 per cent of magnesium carbonate.

Height.	Calcium Carbonate.	Magnesium Carbonate.
50′	97.7	2.3

Microscopical. — The matrix of the rock consists of "mud." Cavities in the rock are lined with calcite crystals, and the organisms are to a large extent represented by calcite infillings.

VAVAU. — At the northern end of the Tonga Group the elliptical plateau of Vavau[2] occurs in association with a number of smaller islets. Three or four limestone terraces are seen at levels of 140, 260–350, and 420–520 feet respectively. The northern edge of Vavau rises to well over 500 feet, and slopes down inland and to the south.

Chemical. — Limestones from the third, second, and first terraces exhibited a close similarity in composition; in each case only about 3 per cent of magnesium carbonate was found.

	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
3d Terrace	Highest Point	97.4	2.6	
	360′	97.0	3.0	.03
2nd Terrace	350′	97.4	2.6	
	310′	96.8	3.2	
1st Terrace	140′	97.2	2.8	

Microscopical. Highest point, north shore. — The section is entirely filled by an alcyonarian showing spicules whose cavities are lined with calcite.

360′. The rock is made up of organisms and organic fragments, lined with an investing layer of fibrous calcite and cemented into a compact rock with a clear mosaic of calcite crystals. The organisms

[1] American Journal of Science, 1900, p. 193; Mem. Mus. Comp. Zoöl., 1902, Vol. XXVI., No. 1, p. 32.

[2] American Journal of Science, 1900, p. 193; Mem. Mus. Comp. Zoöl., 1902, Vol. XXVI. No. 1, p. 33.

comprise coral fragments, Polytrema, Lithothamnion, and much-altered Halimeda.

350′. Similar to the rock from 360 feet, except that the concentric coating to the fragments is rather less prominent.

310′. Consists of Polytrema, coral fragments, Lithothamnion, Gypsina, etc., with a feebly marked concentric coating of fibrous calcite.

140′. *First Terrace.* — Gypsina and Carpenteria can be recognized, but all the aragonite organisms, including the corals, have recrystallized to clear calcite. The matrix consists mostly of "mud," and no fibrous calcite surrounds the organisms.

D. *The Paumotus Group.*

The islands of this group are described by Mr. Agassiz, in connection with the explorations of the "Albatross."[1] He finds that the western part of the Paumotus consists of a partly submerged ledge of older coralliferous limestone covered with a thin modern reef. The land of the Paumotus atolls is built up simultaneously by accumulations of sand both from the lagoon side and also from the sea face. Mr. Agassiz regards this circumstance as characteristic of the group.

MAKATEA (called also Mehetia, Metia, or Aurora Island) is situated in latitude 17° 45′ S., longitude 148° 3′ W., and consists of upraised coralliferous limestone. The greatest elevation is 230 feet, and a central depression exists 50 feet lower than the rim of either face. At the western end of the island four terraces can be traced.

Chemical. — This island gained geological importance owing to the visit of Prof. J. D. Dana, and the fact that the first specimen of dolomitized coral limestone was collected by him from this locality. The specimens from the terraces and central basin, which I have analyzed, show, however, practically no dolomitization, as the percentage of magnesium carbonate in the rocks does not rise above 3.7. This result is interesting as illustrating the partial character of the dolomitization which this island, in common with many others, has undergone.

	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
3rd Terrace		96.5	3.5	
"	200′	97.2	2.8	
"	200′	96.5	3.5	
2nd Terrace		96.5	3.3	.20
Basin	150′	96.3	3.7	

[1] American Journal of Science, 1900, pp. 34–43; Mem. Mus. Comp. Zoöl., 1902, Vol. XXVI. No. 1, p. 18.

Microscopical. 200′. *Third Terrace.* — Figure 4. The slide shows a transverse section of a compound coral whose stereoplasm has been changed to granular crystals of calcite and whose inner and outer walls are now marked by dirt lines. Some of these calcite crystals are clear, but many have an inner kernel of opaque material often roughly parallel to the external boundary of the crystal. This apparent zoning is quite an uncommon feature of calcite in rock sections. Cavities between the septa of the coral and between adjacent organisms have been filled with "mud," which has subsequently crystallized in the form of a muddy mosaic of calcite.

150′. *Basin.* — The rock is largely made up of unaltered Polytrema and other fragments, which have been changed to clear calcite. The matrix of the rock consists of "mud," in which cavities occur lined with scalenohedral crystals of calcite (Figure 5). In one or two of these cavities the scalenohedra are seen to be zoned.

NIAU. — Niau or Greig Island lies in latitude 16° 10′ S., longitude 146° 20′ W., and is the only atoll in the Paumotus, visited by Mr. Agassiz,[1] in which the lagoon is entirely shut off from the sea. The ledge of older limestone forms a rim surrounding the circular lagoon, and is ½ mile wide and 15–20 feet high.

Chemical. — Two specimens were analyzed, both from a height of 20 feet, and were found to be limestones containing 5.0 and 2.7 per cent respectively of magnesium carbonate.

Height.	Calcium Carbonate.	Magnesium Carbonate.
20′	95.0	5.0
20′	97.3	2.7

Microscopical. 20′. — The specimen was collected halfway across the rim of the island, and consists of a section of a large coral with smaller coral fragments. The coral is very fresh, being brown in color, and in places show the centers of calcification very clearly. Some spaces in the coral are filled with "mud" to a certain level, forming horizontal "mud floors," and subsequently scalenohedral crystals of calcite were deposited from solution upon the surfaces of the "mud floors" and also lining the coral walls.

E. The Ladrones.

GUAM. — This island is situated in latitude 13° 30′ S., longitude 145° E. It is mainly volcanic in origin, but the northern half consists of elevated coralliferous limestone with vertical cliffs 100–300 feet in height.

[1] American Journal of Science, 1900, pp. 369–374.

The massif at the southern half of the island is volcanic, and the highest ridge reaches 1000 feet.

Chemical. — Four rocks were analyzed, and were found to contain very little magnesium carbonate, the amounts varying from 1.6 to 3.4 per cent.

	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
Summit of Mount Makama		97.2	2.8	
South side of Apra		96.8	3.4	
	400′	96.5	1.6	1.94
	20′	97.0	3.0	

Microscopical. Summit of Mount Makama. — The matrix of the rock consists of "mud," part of which has been converted into calcite. Many small ellipsoidal fragments occur in the rock, and their shape and size suggest that they may have passed through the bodies of fish.

2. Indian Ocean.

Christmas Island.

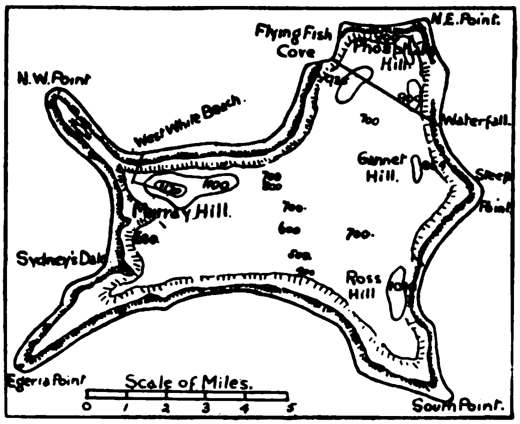
Dr. Andrews has described the structure of the island in detail in his monograph published in 1900 by the Trustees of the Natural History Museum. It will, therefore, not be necessary for me to do more than briefly summarize the chief points in his description. The island lies in the eastern part of the Indian Ocean, in latitude 10° 25′ S., longitude 105° 42′ E., 190 miles south of Java, and 550 miles northeast of Keeling Cocos atoll. The greatest length of the island is 12 miles, the greatest breadth 9 miles, and the total area about 43 square miles. The accompanying map is drawn on a reduced scale from the one published in the monograph. Upon it are marked the localities and lines from which Dr. Andrews obtained the limestones which form part of the subject-matter of this inquiry. The specimens were collected in vertical sequence from the cliffs and slopes, and their heights were carefully noted either by measurement or by the use of an aneroid barometer.

The basis of the island is almost certainly a volcanic peak, upon whose summit and flanks accumulations of tertiary limestones have been deposited. Eruptions, probably submarine, took place from time to time, and the products of eruption were interstratified with the limestones. The earlier eruptive rocks were first trachyte, then basalt, while the latest consisted of beds of palagonite tuff, upon which the great mass of the Miocene (Orbitoidal) limestone rests.

The greater part of the exposed surface of the island consists of a plateau at a general level of about 600–700 feet. Higher ground is found to

the north at Phosphate Hill, which exceeds 900 feet in height, while the highest ground in the island occurs at Murray Hill on the west, where the altitude reaches 1170 feet. During the period of elevation of the central nucleus there were several pauses, as a result of which fringing reefs occur at various levels. These are now represented by a series of four slopes, or inland cliffs, continuous nearly all round the island.

1. The newest or present fringing reef.
2. The shore terrace, 50 feet in height.
3. The first inland cliff, from 80–300 feet in height.
4. The second inland cliff, ranging from 320–600 feet in height.



Christmas Island.

Faulting and slipping have occurred fairly extensively, especially on the rim of the island, and it is largely owing to this cause that the terraces are not quite continuous. This is particularly the case on the northwest at Flying Fish Cove, where a fairly complete section is seen from the older Eocene and Oligocene limestones at the base up to the Miocene rocks at the top of the cliff. Specimens have been examined which illustrate sections both from the older rocks and also from the older and newer inland cliffs or fringing reefs. The results of the examination of these rocks will now be given in the order mentioned.

Older Rocks (Eocene to Miocene).

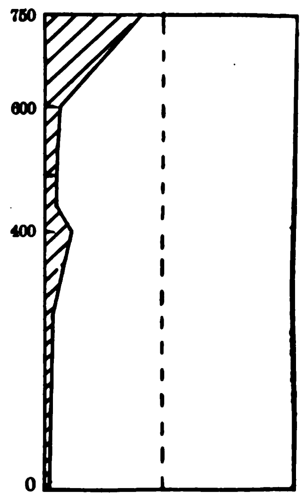
Flying Fish Cove. *Chemical.* — At this part of the island a good section occurs in the sea cliff. Rocks of Eocene or Oligocene age are exposed at the sea level, while on the plateau above, corals occur to

which a Miocene age has been assigned. The continuity of the limestones is broken by two fairly thick beds of basalt, both probably of submarine origin. The beds of basalt are separated by a considerable thickness of a middle yellow limestone, probably of Oligocene or lower Miocene age. The specimens analyzed from the sea cliff at Flying Fish Cove were collected at definite heights from the sea-level up to 750 feet, both from the north and south ends of the Cove. Of these, the uppermost rock, No. 664, from a height of 750 feet, contains 36.2 per cent of magnesium carbonate. All the rest are limestones, most

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
664	750′	63.8	36.2	—
991	600′	95.7	4.3	—
827	550′	94.6	5.4	—
521	530′	96.1	3.9	—
963	500′	97.29	2.71	—
549	500′	96.8	3.4	.03
571	480′	97.0	3.0	—
845	450′	97.4	2.6	—
595	400′	91.2	8.0	.80
840	275′	96.8	2.5	.70
2	0′	96.7	2.6	.72

FLYING FISH COVE.

OLDER ROCKS.



of which contain only from 3 to 4 per cent of that compound, with the exception of No. 595, in which 8 per cent is present. Insoluble matter is almost unrepresented in the higher rocks, — No. 549 contains .03 per cent, — but the three oldest limestones have from .7 to .8 per cent of insoluble residue. This circumstance is probably due to their close association with the two beds of basalt which occur in this part of the island.

Microscopical. No. 521. — An orbitoidal limestone containing Carpenteria, Orbitolites, Lithothamnion, and the cast of a coral in "mud." Much of the section consists of "mud," but some has altered to clear calcite, and in this part the organisms are represented by dirt lines.

No. 963. The organic fragments in this limestone are quite fresh, and consist of Carpenteria, *Polytrema miniaceum*, Amphistegina, alcyonarian spicules, echinid spines, and Lithothamnion. The organisms are for the most part invested with a coating of fibrous muddy calcite, and the remaining spaces have been filled with a mosaic of clear calcite crystals.

No. 549. An orbitoidal limestone having a matrix of calcite. An incrusting deposit of calcite partially fills some cavities and cracks occurring in the rock.

No. 571. An orbitoidal limestone similar to the last, but containing more "mud" in the matrix. Some of the organisms have been altered to a brownish silt. Acute crystals of calcite project from their margins, and adjoining fragments have been cemented subsequently by large crystals of calcite.

No. 845. A Lithothamnion limestone in which many of the organisms are represented by pseudomorphs in calcite.

No. 595. Globigerina and small fragments of Carpenteria are abundant in this limestone, while calcite crystals fill cracks in the rock, and serve to cement numerous fragments of yellow palagonite.

No. 840. A limestone containing Gypsina, Halimeda (?), and echinid spines. Minute volcanic fragments are scattered through the rock, which is rather cavernous.

No. 2. An orbitoidal limestone containing, in addition, well-preserved Gypsina, Amphistegina, and Lithothamnion.

Above Flying Fish Cove. *Chemical.* — Proceeding inland from No. 664 at the top of the sea cliff, the level falls slightly at first, and three specimens collected along this gentle slope have been analyzed. No. 663 is from about the same level as No. 664 — namely, 750 feet — but is found to contain only 1.7 per cent of magnesium carbonate, while a little further inland, from a level of 710 feet (No. 657), yields 25 per cent. Quite close to this last limestone the surface of the ground is covered with a chalk-like deposit in which occur harder nodules. The centers of these nodules, represented by No. 658 A, consist of a compact limestone containing only 2 to 3 per cent of magnesium carbonate, while the soft crumbling exterior (No. 658 B) is highly dolomitic, containing no less than 39.5 per cent of magnesium carbonate. The association of these two rocks is very interesting, and would seem to suggest that the dolomitic rock may, in this case, arise by the concentration of magnesium carbonate, owing to the superior solubility of calcium carbonate in percolating water containing atmospheric carbon dioxide. Further back from

the sea cliff the ground rises rather sharply to a height of 880 feet, and an analysis made at that level (No. 514) yields 40.67 per cent of magnesium carbonate, while some distance to the south-west (No. 1011), at a height of 800 feet, is also dolomitic containing 35.2 per cent of magnesium carbonate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
663	750′	98.3	1.7
657	710′	97.5	2.5
658 A	710′	97.5	2.5
658 B	710′	60.5	39.5
514	880′	59.33	40.67
1011	800′	64.8	35.2

Microscopical. No. 658 A. — The rock consists of small fragments of well-preserved organisms, such as Carpenteria, Lithothamnion, etc., set in a gray silty calcite matrix. The rock is probably a recrystallized calcareous "mud."

No. 658 B. The slide consists almost entirely of idiomorphic crystals of dolomite, having dark centers. Most of the organisms have been obliterated, but one or two specimens of Amphistegina, and possibly Polytrema, occur. In some places scalenohedral crystals project from the surfaces of organic fragments.

No. 514. The section consists largely of rhombohedra of dolomite, in many of whose centers are dark materials caught up in an early stage of crystallization, and hence giving the appearance of zoning. All organisms have disappeared, except possibly where a meandrine arrangement of opaque or silty matter may represent a former organism, such as coral or Polytrema.

No. 1011. A dolomitic limestone in which many of the crystals have dark centers. Some spaces in the rock have, since dolomitization, been filled with secondary calcite.

SOUTHEAST OF PHOSPHATE HILL. — The section of the older rocks at this spot is not complete. The upper 200 feet is clear, and at one place near the shore, erosion has caused the Eocene or Oligocene limestones to be exposed below a bed of basalt. Between these points three terraces or fringing reefs occur, and mask the older rocks. The average slope of the cliffs towards the sea is about 30°.

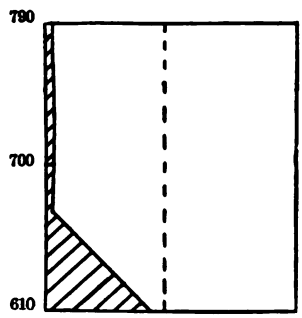
Chemical. — Miocene rocks are exposed from the top of the cliff at 790 feet down to 610 feet. Analyses made between these heights show that the upper 120 feet consists entirely of limestones, with about 3 per cent of magnesium carbonate. At the level of 640 feet the percentage has

increased to 27.7, while at 610 feet no less than 42.7 per cent of magnesium carbonate is found. At this point the section of the older rocks is masked by terraces or fringing reefs, which form a cloak of newer material, only pierced at one point above sea-level, where an Eocene or Oligocene limestone occurs (No. 635) having 3.9 per cent of magnesium carbonate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
610	790′	97.0	3.0
611	760′	97.3	2.7
612	730′	96.8	3.2
613	700′	97.1	2.9
614	670′	97.7	2.3
615	640′	72.3	27.7
616	610′	57.3	42.7
635	0′	96.1	3.9

SOUTH-EAST
OF PHOSPHATE HILL.

OLDER ROCKS.



Microscopical. No. 610. — A limestone containing an unrolled fragment of Orbitoides, together with Polytrema, Amphistegina, and a little yellow isotropic material, possibly palagonite. The organisms are well preserved, the rock is cavernous, and the semi-opaque matrix is seen under the high power to be crystalline.

No. 615. A very cavernous dolomite showing no traces of organisms, except a few meandrine forms. The spaces and cavities in the rock have been, to a great extent, filled with large slightly yellow crystals of secondary calcite.

No. 616. A uniform, compact, fine-grained dolomite, showing a few small fragments of Lithothamnion, and here and there dark meandrine patches suggesting the former presence of Polytrema.

SYDNEY'S DALE. — This dale is a gorge on the west coast, originally determined by a fault line, and further excavated by a stream which runs through it. In this dale Oligocene or Eocene beds occur, containing the oldest type of Orbitoides met with at Flying Fish Cove.

Chemical. — Three limestones were analyzed: No. 308, from a height of 350 feet, contains 39.22 per cent of magnesium carbonate, while No.

348 and No. 350, from heights of 325 and 310 feet, contain respectively only 2.6 and 5.2 per cent of that compound.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Calcium Phosphate.
308	350′	60.63	39.22	.15
348	325′	97.4	2.6	
350	310′	94.8	5.2	

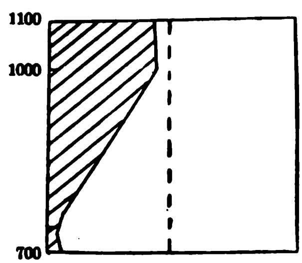
Microscopical. No. 348. — A rather cavernous limestone, largely consisting of crystalline semi-opaque cement, and in which Globigerina occurs rather plentifully.

Rocks from the Interior of the Island (Miocene ?).

LINE ON THE ROAD TO MURRAY HILL. — This road starts from a point where it meets another road at right angles to it running down to West White Beach. The limestones were collected in vertical sequence up the slope, from 650 feet to 1100 feet, almost at the summit of Murray Hill.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
378	1100′	60.34	40.02
379	1000′	59.8	40.2
360	725′	96.0	4.0
356	690′	97.1	2.9
355	650′	95.7	4.3

MURRAY HILL.



Chemical. — The two highest specimens, No. 378 and No. 379, from heights of 1100 and 1000 feet respectively, contain about 40 per cent of magnesium carbonate, but the remaining three specimens are limestones, in which the amount does not reach 5 per cent.

Microscopical. No. 378. — Lithothamnion can still be recognized, and a gray meandrine dolomitic "silt" suggests the former presence of corals. The amount of finely crystalline dolomite is very large, but cavities are lined with clear rhombohedra, and no zoning is seen.

No. 360. Almost entirely composed of very small rounded or fusiform fragments, with a few larger rounded pieces, cemented by clear scalenohedral crystals of calcite. The appearance of these fragments

suggests that they may represent the excrement of fishes, and this idea is supported by their general uniformity of size and fusiform shape.

Cliffs over West White Beach. — These limestones, only two in number, are from the road leading down to West White Beach. This road is joined at right angles by the road to Murray Hill.

Chemical. — Two analyses were made of rocks from 700 and 600 feet, and these contained 14.3 and 3.3 per cent of magnesium carbonate respectively.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
365	700′	85.7	14.3
373	600′	96.7	3.3

Microscopical. No. 365. — The rock is made up of fragments of organisms which for the most part are well preserved. The aragonite organism Halimeda has been, however, changed to calcite and the cavities in the rock are filled with the same mineral.

Phosphate Hill Road. — This road starts just below the 800 feet contour inland from Flying Fish Cove, and at this point is joined by a road going south-east from Flying Fish Cove to the Waterfall. It proceeds to Phosphate Hill along gently rising ground.

Chemical. — The highest specimen, No. 815, contains 13 per cent of magnesium carbonate. Twenty feet lower, No. 816 yields 7.4 per cent, and No. 817, from a height of 780 feet, contains only 3 per cent of magnesium carbonate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
815	820′	87.0	13.0
816	800′	92.6	7 4
817	780′	97.0	3.0

Microscopical. No. 815. — A rock made up of large opaque fragments set in a semi-opaque matrix. Amphistegina is common, and the organisms as a whole appear to be unaltered.

Southeast Road between Flying Fish Cove and the Waterfall. — This road starts from a point at 700 feet above Flying Fish Cove. It then rises to 900 feet, falling to 820 feet, again rising to 900 feet and falling to the south-east towards the Waterfall. Specimens, from No. 709 to No. 700, were collected along this road.

Chemical. — One limestone, No. 707, from the first slope nearest Flying Fish Cove, is dolomitic, but the remaining nine specimens, collected

at intervals along the road, do not contain more than about 5 per cent of magnesium carbonate.

Microscopical. No. 708. — A meandrine cast of a coral in calcite and sections of *Polytrema planum* fill most of the slide. The semi-opaque matrix is seen under the high power to consist of calcite crystals.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
709	700′	94.8	5.2
708	700′	95.1	4.9
707	880′	66.4	33.6
706	900′	95.0	5.0
705	900′	94.9	5.1
704	870′	95.9	4.1
703	820′	95.3	4.7
702	870′	96.8	3.2
701	900′	96.7	3.3
700	790′	96.0	4.0

No. 705. A section of a fragmental limestone containing perfectly fresh-looking and unrolled *Orbitoides neo-dispansa*, besides Polytrema Amphistegina, Orbitolites, Carpenteria, Lithothamnion, set in a matrix of calcite.

Isolated Analyses from the Interior of the Island.

Vicinity of Phosphate Hill. — Three specimens were collected from the slopes of the hill just below the bed of phosphate which forms the capping to the summit. All three specimens are dolomitic, but it is an interesting circumstance, considering their relation to the phosphatic capping, that none of them give any appreciable reaction for phosphate with ammonium molybdate.

Chemical.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
800	850′	65 05	34.77
804		67.88	31.96
811		61.79	37.96

Microscopical. No. 800. Figure 7. — A dolomitic limestone in which the matrix consists of crystals of dolomite. Most of the organisms are coated with minute acute crystals, probably calcite. The echinid spines and some of the sections of Amphistegina appear almost unaltered, but many of the organisms have partially recrystallized, and rhombs of dolomite have invaded the organisms from without inwards. This is well seen in several longitudinal and transverse sections of Lithothamnion, while a Halimeda has some of its tubules unaltered, but in others rhombs of dolomite have been formed, and destroyed the boundary of the walls of the tubules. A cavity in the rock has been filled with clear crystals of dolomite, while zoning by included muddy material is well seen in those crystals formed by the recrystallization of Lithothamnion.

No. 811. A dolomitic limestone, with a fair quantity of semi-opaque material. Much of the slide, however, consists of rhombohedra of dolomite, with dark centers parallel to the outside boundary, and representing "silt" caught up during recrystallization. Cavities are numerous, and the walls of these are lined with clear crystals of dolomite.

East Coast. — One specimen has been analyzed from the summit of the upper cliff on the East Coast at a height of 800 feet.

Chemical. — It is a limestone containing only 2.44 per cent of magnesium carbonate and .15 per cent of calcium phosphate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Calcium Phosphate.
134	800′	97.56	2.44	.15

Microscopical. No. 134. — This is a limestone containing many sections of *Polytrema planum*, while Lithothamnion also occurs. Semi-opaque material is present in the matrix, while clear calcite fills some of the cavities.

Second Inland Cliffs (Older fringing Reefs — Lower Pliocene ?).

Southeast of Phosphate Hill. — This is one of the fringing reefs which partly mask the older rocks in this section. It occurs between the levels of 600 and 300 feet.

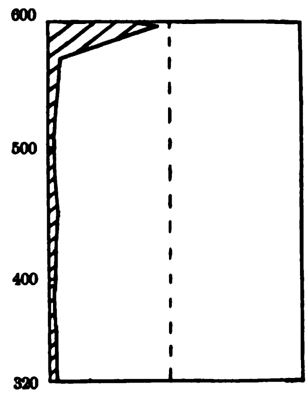
Chemical. — No. 617 occurs on the subhorizontal flat marking the top of the reef or cliff, and contains 34.1 per cent of magnesium carbonate. No. 618 was found at the outer edge of the flat at the top of the cliff, and on analysis yields no less than 43.30 per cent of magnesium carbonate. This is the most highly dolomitized of any of the limestones

which have been analyzed. It is possible that both these rocks may be derived from the older dolomitic limestones occurring in the cliff above. The remainder of the analyses in this section are those of limestones, in which the amount of magnesium carbonate does not rise above 4 per cent.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
617	600′	65.9	34.1	—
618	600′	56.82	43.30	—
619	570′	97.6	2.4	—
620	540′	96.3	3.7	—
621	510′	96.8	3.2	—
622	480′	97.1	2.9	—
623	450′	96.1	3.9	—
624	420′	96.3	3.7	—
625	390′	97.5	2.5	.024
626	360′	96.6	3.4	—
627	320′	96.0	4.0	—

SOUTH-EAST OF PHOSPHATE HILL.

SECOND INLAND CLIFF.



Microscopical. No. 618. — A cavernous rock, containing hollow casts of Amphistegina. The only recognizable organism is a much altered Lithothamnion. The matrix consists chiefly of clear rhombohedral crystals of dolomite, a few of which show zoning by included material.

No. 619. This appears to be a rubble rock. Small fragments of what looks like a dolomitic limestone are mixed with other darker limestone fragments. One small rounded augite is present, while in one of the fragments a piece of coral occurs, having its organic structure well preserved.

No. 623. A very close-grained compact limestone, containing a few rhombohedral crystals. Very few recognizable organisms are present in this rock.

WEST WHITE BEACH. — This fringing reef forms a shallow cliff between the levels of 500 and 400 feet at West White Beach, about a mile northwest of Murray Hill.

Chemical. — Four analyses were made, and the rocks were found to be limestones, containing only a minute quantity of insoluble material, and from 2.6 to 5.8 per cent of magnesium carbonate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
354	500′	94.3	5.7	.024
374	500′	94.2	5.8	
304	470′	95.5	4.5	.024
368	440′	97.4	2.6	

NORTH-EAST POINT. — A specimen from the summit, at height of 600 feet, yielded 1.72 per cent of magnesium carbonate, and .2 per cent of calcium phosphate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Calcium Phosphate.
179	600′	91.72	1.72	.20

Microscopical. — A limestone, with a matrix largely of silt, containing unaltered Lithothamnion, Carpenteria, Polytrema, Truncatulina, and Amphistegina. Cracks in the rock have been filled with a mosaic of secondary calcite, while some cavities are lined with scalenohedral crystals.

First Inland Cliff (Newer fringing Reef. Late Pliocene ?).

NORTH OF FLYING FISH COVE. — At Flying Fish Cove the fringing reefs are not represented, but a little to the north the shore cliff is found, and also the first inland cliff, which forms a well-marked feature between the heights of about 60 and 300 feet.

Chemical. — All the rocks analyzed from this cliff are limestones, but at levels of 250 feet (No. 211), 200 feet (No. 208), and 50–60 feet (No. 200) the amount of magnesium carbonate present rises to 10.9, 8.5, and 10.5 per cent respectively. In the remaining limestones the amount varies from 2 to 4 per cent.

Microscopical. No. 1032. — A rock composed of fragments from the reef. Calcareous algæ, Polytrema, and echinid spines occur, but a large part of the slide is occupied by a section of a compound coral, whose organic structure is well preserved. Crystals of aragonite are in optical continuity with the coral fibers, and wholly or partly fill the interstices. The residual space is filled with a clear mosaic of calcite, which looks as if it has arisen largely at the expense of the aragonite. In some parts of the slide organic fragments are invested with a coating of fibrous calcite crystals. Some of the organisms are represented only by

dirt lines round the margins of the organisms, the interior being recrystallized calcite.

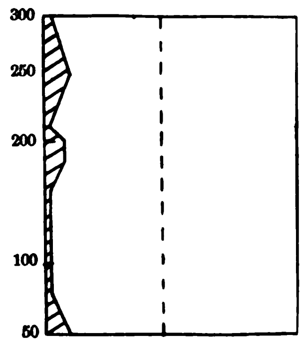
No. 211. Most of the slide is occupied by the section of a coral, whose spaces are filled partly with "mud," partly with aragonite crystals continuous with the coral fibers, and partly with clear calcite.

No. 209. Large coral fragments and other organisms make up the bulk of the rock, and are cemented together by a deposit of fibrous calcite crystals.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
1032A	300′	97.7	2.3	—
1032	300′	95.8	4.2	—
211	250′	89.1	10.9	—
209	210′	96.9	3.1	—
208	200′	91.5	8.5	.024
206	160′	97.3	2.7	—
203	90′	98.0	2.0	—
201	80′	97.1	2.9	—
200	50–60′	89.5	10.5	—

NORTH OF FLYING FISH COVE.

FIRST INLAND CLIFF.



No. 208. Coral fragments, sections of lamellibranchs, and other organisms, including several specimens of Globigerina, are set in a matrix of dark calcareous "mud." In one part of the slide fibrous calcite invests the organisms.

No. 202. A limestone with a muddy matrix, containing coral fragments and many specimens of Globigerina. Muddy, fibrous incrusting crystals of calcite invest some fragments.

No. 200. A limestone, largely composed of coral fragments, with aragonite crystals in some cavities. A large amount of fibrous cementing calcite occurs. Round Lithothamnion, scalenohedral crystals were first formed, and then an outer layer of fibrous calcite, while a plate of calcite has surrounded an echinid spine, the deposited material being in optical continuity with the calcite of the organism.

SOUTH-EAST OF PHOSPHATE HILL. — Below the second inland cliff another cliff occurs between the heights of 200 and 300 feet, which forms the newer fringing reef in this part of the island.

Chemical. — Two analyses only have been made. Both the rocks are limestones, and contain 2.3 and 3.0 per cent of magnesium carbonate respectively.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
630	270′	97.0	3.0	.074
631	220′	97.7	2.3	

Microscopical. No. 630. — A somewhat cavernous limestone, whose matrix consists of calcite. A fair number of rhombohedral crystals occur, some of which have dark centers. The organic fragments are small and badly preserved, and are represented by an interior of calcite with dirt lines round the external margins of the organisms.

East Coast. — Steep Point. — The reef here makes a vertical cliff between the levels of 200 and 300 feet.

Chemical. — All the rocks are limestones with magnesium carbonate in amounts varying from 2.2 to 6.7 per cent.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
1010	300′	96.9	3.1	—
1009	290′	93.3	6.7	—
1008	275′	95.8	4.2	—
1007	260′	95.5	4.5	—
1006	250′	95.4	4.6	—
1004	230′	96.8	3.2	.026
1003	215′	97.8	2.2	—
1002	200′	95.0	5.0	—
1001	200′	97.1	2.9	—

Microscopical. No. 1006. — A fragmental rock made up of pieces of older rocks containing fragments of corals and of Orbitoides. These fragments are cemented with a matrix first of fibrous calcite, the consolidation being completed with a granular mosaic of calcite crystals.

No. 1005. A limestone containing much opaque "mud," in which casts of simple corals are preserved. Carpenteria is abundant in this rock.

West White Beach. — The rocks here form a low cliff between the heights of 250 and 380 feet.

Chemical. — Three analyses show that magnesium carbonate is present in amounts varying from 2.1 to 5.7 per cent, while the fourth limestone from 300 feet contains 11.2 per cent of magnesium carbonate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.	Insoluble Residue.
303	375′	95.5	4.5	
372	300′	88.8	11.2	
305	280′	94.3	5.7	.04
371	250′	97.9	2.1	

Microscopical. No. 372. Figure III. — A fragmental limestone containing corals, gastropods, echinid spines, Orbitolites, Lithothamnion, and Halimeda. The coral has aragonite crystals in optical continuity with its own fibers, while scalenohedra incrust the Lithothamnion. All the organisms are cemented with fibrous calcite radiating from each organism, and interfering with the deposit from an adjacent fragment, so as to produce a polygonal effect in the rock section.

South End of East Coast. *Chemical.* — One analysis from a height of 400 feet yields 16.9 per cent of magnesium carbonate.

Number.	Height.	Calcium Carbonate.	Magnesium Carbonate.
131	400′	83.1	16.9

Microscopical. — A dolomitic limestone whose matrix consists largely of rhombohedral crystals with cavernous spaces. The organisms consist almost entirely of *Polytrema miniaceum.*

III. Chemical Summary.

In attempting to summarize the chemical results obtained from a study of limestones from fifteen raised coral islands, it is found that the facts group themselves most naturally round three points. These are: — (A) The distribution of magnesium carbonate in the limestones, (B) the amount of calcium phosphate they contain, and (C) the extent to which insoluble residue is associated with them.

A. Chemical analysis shows that certain of the islands have been dolomitized from top to bottom. Ngillingillah and Vatu Vara belong to this class. Only one limestone from Yathata has been analyzed, and one from Kambara, but both are found to be highly dolomitic. Examination of several islands fails to show any appreciable dolomitization.

Niue, Vavau, Tongatábu, Niau, Guam, and Makatea are of this type. In the case of Makatea (Metia), however, Dana and Silliman have recorded the occurrence of dolomitic limestone, and it is possible that an examination of other specimens may show that some of the islands mentioned do contain dolomitic rocks. Limestones containing little or no magnesium carbonate are found associated with dolomitic limestones in Christmas Island, Mango, Namuka, and Eua.

On examining rocks from these islands it is found that dolomitization may occur at several horizons. In Namuka, the lowest and oldest rock is dolomitized, while in Christmas Island one of the Oligocene or Eocene rocks of Sydney's Dale, from a height of 350 feet, is highly dolomitic. Again, at Christmas Island, in the cliff section, east of Phosphate Hill, dolomite occurs in the Miocene rocks at a level of 600–640 feet. At Mango, limestones are only found at three heights, 370, and 310, and 298 feet; all the remaining specimens being highly dolomitic. Perhaps the occurrence of dolomite is most usual at the highest points of the islands. This is found to be particularly true of Christmas Island, where the three highest hills are all dolomitized, as are the tops of Mango, Ngillingillah, and Vatu Vara, while dolomitic limestones are found near to the summits of Yathata and Kambara.

Very little magnesium carbonate is, as a rule, found in the limestones from the newer reefs fringing the raised coral islands. In certain cases as much as 10 or 11 per cent of magnesium carbonate is found without the formation of recognizable crystals of dolomite, but in only two instances have highly dolomitic limestones been found among the rocks of the inland cliffs or terraces. At Christmas Island, the top part of the upper inland cliff south-east of Phosphate Hill is found to be highly dolomitic, while the other example is from the first inland cliff or terrace of the island of Eua. But in these cases it is difficult to say with certainty whether the rocks belong to a true fringing reef, a ledge in the older rocks cut back by the sea during a pause in elevation, or a submarine talus composed of the débris of the older rocks above it.

Many of the dolomitic limestones, in composition, approach to, and even slightly exceed, 40 per cent of magnesium carbonate. But it is an interesting circumstance that, up to the present, no rock having the composition of a true dolomite has yet been met with among the limestones from coral islands. The maximum value for magnesium carbonate yet recorded is 43.3 per cent, from one of the Christmas Island rocks.

B. More or less extensive deposits of guano are found here and there

among the coral islands of the Pacific. At Christmas Island, the summits of Murray, Phosphate, and Ross Hills, according to Dr. C. W. Andrews, were low islands rising from the lagoon during Miopliocene times, and were covered with guano deposits. Percolating water has, since then, changed the subjacent limestone to almost pure calcium phosphate. At Phosphate Hill, the deposit is in places 10 feet thick, while at Murray Hill, a phosphate of aluminum and iron occurs, probably derived from the alteration of some volcanic rock. This seems to be comparable with Mr. Teall's description of the phosphatization of the trachyte of Clipperton Atoll.[1] Besides the massive deposits of phosphate, a small quantity occurs almost universally among all the limestones of coral islands. The amount has never been found to exceed .3 per cent, and is often much less. Its constant character is no doubt due to the small quantity which the organisms assimilate from the sea-water in building up their skeletons.

C. Organic residue is only found in the most recent and unaltered rocks, and is then present in amount up to 1.5 per cent. During the processes of consolidation and recrystallization of the rocks, the organic matter appears to be dissipated, probably to a great extent in the form of carbon-dioxide, and carried off by percolating water.

Insoluble inorganic residue is present in almost inappreciable amount in the very large majority of the rocks. As a rule, the insoluble residue varies from .01 to .20 per cent.

In a few of the limestones immediately associated with volcanic rocks such as occur in Christmas Island, Mango, and Guam, the amount of residue is larger, and in one case exceeds 4 per cent. This increase of insoluble matter is doubtless due to the proximity of the volcanic material. With the exceptions cited, the almost entire absence of inorganic residue is a marked feature of these oceanic coral islands. These facts seem to be significant, especially when it is considered that in deep-sea deposits, even in the neighborhood of coral islands, the amount of insoluble residue rarely falls below 1 per cent, and often rises to 20 per cent.[2]

In the case of the Singatoka cliffs, where the insoluble residue rises to nearly 2.5 per cent, the large amount is probably due to the formation of the limestone on the margin of the large island of Viti Levu, consisting almost entirely of igneous rocks.

[1] Q. J. G. S., 1898, pp. 230–232.

[2] Report of Scientific Results of the Challenger Expedition, Appendix III., pp. 445–496.

Allowing for the disturbing effect in the proximity of volcanic rocks, it will be noticed that absence of insoluble residue may be regarded as characteristic of coral limestones formed in shallow water and under oceanic conditions, while deep-sea limestones and fringing reefs to great land masses normally contain upwards of 1 per cent of insoluble residue. It seems possible that these facts may be found to be of use in interpreting the mode of origin of some of the older limestones of the earth's crust.

The mineralogical and structural changes which take place in coral limestones are consequent upon certain chemical changes in the rocks, which may be briefly considered at this point. The formation of the investing fibrous deposit of calcite round organic fragments, noticed in rocks from some of the fringing reefs (Figure 3), is probably due to the coating of fragments with a deposit of calcium carbonate formed on a beach by the evaporation of sea-water on the recession of the tide. The carbon dioxide present in the water holds a certain amount of calcium carbonate in solution. This is precipitated when exposed to the air, owing to the evaporation of the water and the loss of carbon dioxide. A macroscopic study of the limestones also shows that a certain amount of solution must have taken place since the rocks have been upraised. It is noticed that many cavities in the limestones have been more or less filled with a stalagmitic coating of calcite, and in certain cases, with dolomite. These deposits are no doubt due to the solvent properties of rain water bearing carbon dioxide in solution, and the precipitation of the dissolved carbonates on the escape of the carbon dioxide. While subaerial changes such as these do undoubtedly occur, yet most of the chemical changes have probably taken place below the sea-level.

A study of the thin sections of the limestones shows that aragonite may arise from the alteration of calcareous mud, which fills certain cavities in the corals, while it is occasionally deposited in clear crystals directly from solution. Again, calcite may be formed by the alteration both of calcareous muds and of aragonite crystals, while under other circumstances it is found deposited directly from solution.

These processes require that the calcium carbonate shall first be dissolved in the sea-water, and, secondly, that under suitable conditions, it shall pass out of solution, and form a crystalline deposit. The solubility of calcium carbonate in sea-water is extremely small, and has been variously estimated at from 1 part in 10,000 to 1 part in 136,000. In all probability the solution is largely increased by the aid of carbon dioxide dissolved in the sea-water.

Messrs. Cornish and Kendall[1] have determined the relative solubility of aragonite and calcite organisms in water containing carbon dioxide, and their experiments show how readily aragonite organisms are disintegrated under these conditions.

The great abundance of animal life in and around coral reefs might help to supply the carbon dioxide, which would be augmented on the death and decay of both animals and plants. In some such way as this, calcium carbonate in the rocks of the reef may be dissolved, and the condition for the deposition of the dissolved carbonate is the local removal of the carbon dioxide. It is not easy to explain how this removal can be effected, but it is possibly due to the presence in large numbers of excessively minute algæ, whose absorption of carbon dioxide may help to bring about the precipitation of the calcium carbonate. As a rule, when calcium carbonate is deposited from cold water calcite alone is formed, while aragonite is deposited from hot solutions. But in coral limestones both calcite and aragonite are deposited from sea-water at the ordinary temperature, under suitable conditions. The physical and chemical properties of the organism on which the deposit is made, seem to have a determining influence on the particular form of calcium carbonate which is eventually formed.

With regard to the mechanism of the chemical change from calcite to dolomite, very little is known. It would seem, however, that under certain conditions magnesium sulphate or chloride from sea-water can replace a certain amount of calcium carbonate in a limestone, and form the double carbonate dolomite. This point will be raised in the conclusion, when discussing the results of Klement's experiments.

IV. Summary of Structural and Mineralogical Changes.

In this part of the work an attempt has been made to trace the sequence of the structural and mineralogical changes which the rocks have undergone. This sequence is described as far as possible in the order in which the changes probably occurred.

Under the microscope it is found that the rocks which have best preserved their original structures, and in which fewest secondary changes have supervened, are those from the fringing reefs of such islands as Niue, Vavau, and Christmas Island.

A section of a coral from one of these reefs shows the centers of calcification and spicular structure well developed, while the cavities

[1] Geological Magazine, 1888, pp. 66–73.

of the coral are empty or partially filled with a fine calcareous "mud" derived from the disintegration of reef organisms.

In a slightly altered coral it is noticed that the centers of calcification are less marked, and the "mud" in the cavities of the coral has been partially recrystallized.

A section of such a coral is seen in Figure 1, from the first terrace of Niue at a height of 80 feet.

Corals have been shown to be built up of aragonite fibers, and the spicular character of the skeleton seems to determine the mode of crys-

FIG. 1.

NIUE, 80 feet. Section of a reef-forming coral showing spicular structure and centers of calcification. Cavities are partly filled with a dark mud which in places has altered to crystals of aragonite in crystallographic continuity with the fibers of the coral. × 30.

tallization of the "mud." Lining the walls of the coral the "mud" is seen to have changed to long prismatic crystals of aragonite, deposited in crystallographic and optical continuity with the coral fibers. The aragonite crystals formed from "mud" are generally to be distinguished from the clear material deposited immediately from solution, by the presence of numerous opaque particles caught up in the crystals. Both types are met with in the limestones, but the aragonite deposited di-

rectly from solution occurs much less frequently than that formed by the recrystallization of a calcareous "mud."

Another point of difference is that crystals deposited from solution grow from the walls of the cavity, and if they entirely fill it the crystals meet in the center in a serrated line, resembling the "comb structure" of a mineral vein. In a clarified "mud" no such definite arrangement of the crystals can be traced. A study of thin sections of rocks from coral islands seems to show that when crystallization

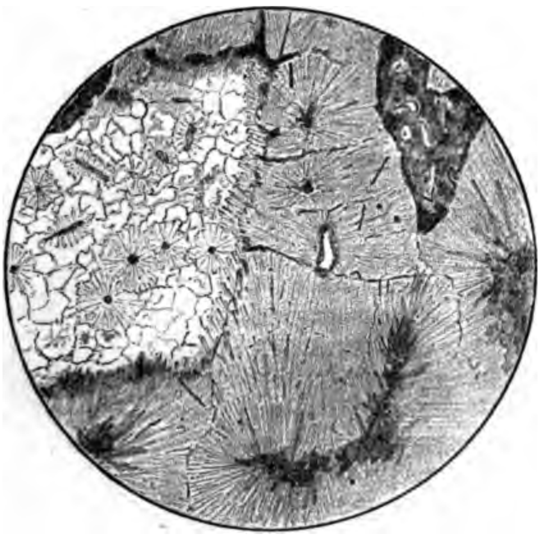


FIG. 2.

NIUE, 200 feet. Some cavities in the coral are filled with "mud," while others have recrystallized. Aragonite has formed on the coral wall and round the tubes of boring algæ, but calcite fills the remainder of the cavity. The spicular character of the coral is well seen. × 80.

occurs, either of a "mud" or from solution, calcite is in general the mineral which is first formed. Aragonite has been found almost exclusively as a lining to the cavities of corals whose spicular structure seems favorable to its formation. Figure 2 represents a section of a reef forming coral from the third terrace of Niue at a height of 200 feet.

Some of the "mud-filled" cavities remained unaltered, but others have been recrystallized. In the more central parts of these cavities the "mud" has crystallized as a granular mosaic of calcite, except round the tubes of boring algæ which are surrounded with radiating crystals,

probably consisting of aragonite. It will be noticed that the "mud" lining the coral walls has crystallized in prismatic needles of aragonite deposited in optical continuity with the fibers of the coral.

The above description represents the appearances of the less altered reef-forming corals. The more commonly occurring constituents of the limestones are, however, compacted "coral sand," detrital fragments of organisms, and a certain amount of rubble rock. A section of a compacted "coral sand" is composed of organic fragments from the reef.

FIG. 3.

CHRISTMAS ISLAND, No. 372. (After boiling with cobalt nitrate.) The aragonite organisms, corals, gastropods, and Halimeda, as well as the aragonite crystals in the coral cavities, are stained pink. The calcite organisms, Orbitolites, echinid spines, and Lithothamnion, together with the fibrous calcite cement, are quite unstained. × 30.

As a rule, it shows aragonitic organisms such as coral fragments, Halimeda, gastropods, etc., together with organisms having calcite skeletons, such as most of the Foraminifera, echinid spines, Lithothamnion, etc.

The organisms are often fragmentary, and are cemented together by a matrix consisting either of "mud" or of calcite. The calcite may exist in two forms. The more usual is a somewhat clear granular mosaic of crystals, but frequently it coats the organisms with an investing layer of long fibrous crystals. A good example of the latter is seen in Figure

3, which consists of a section of a "coral sand" from the lower inland cliff of Christmas Island. The fibrous crystals of the matrix which radiate from adjacent organisms meet along straight lines and give a polygonal appearance to the rock section. This deposit of fibrous calcium carbonate was formed from solution probably on a beach between high and low tide marks. It could only be identified with certainty as calcite after the application of Meigen's staining method described above. After boiling with cobalt nitrate solution, it was noticed that

FIG. 4.

MAKATEA. Third terrace. The substance of the coral has been replaced by crystals of calcite. The coral walls are represented by "dirt lines," while the "mud-filled" cavities have been partially recrystallized. Many of the calcite crystals have dark centers. × 30.

the coral and deposited aragonite crystals, as well as Halimeda and the gastropod, with included aragonite, had been stained, while the echinid spine, Orbitolites, and Lithothamnion, together with the fibrous crystalline matrix, remained quite unaffected.

In the newer rocks, of which the first three illustrations may be taken as examples, it will be noticed that the skeletons of all the organisms remain practically unaltered. When, however, older rocks are examined, it is seen that some of the organisms no longer have a fresh appearance. The tendency of the unstable form aragonite to pass over to the more

stable form calcite has resulted either in the gradual conversion of the aragonite organisms into granular calcite without loss of the external boundaries, or, as frequently happens, this change is attended by the complete disintegration and obliteration of the organisms.

Figure 4 is in illustration of the first alternative.

It is a transverse section of a reef-forming coral from the third terrace of Makatea, and shows a coral whose cavity was originally filled with "mud." The stereoplasm has been replaced by a mosaic of almost clear

FIG. 5.

MANGO, 370 feet. A fragmental limestone partially recrystallized. Most of the matrix is "mud," but some has changed to calcite. Calcite organisms, such as Lithothamnion and echinid spines, remain unaltered; but aragonite organisms are represented by clear calcite and dirt lines round their external boundaries. × 30.

calcite. The external wall of the coral can now be traced only by a thin dirt line, which possibly represents the impurities and organic matter extruded during the process of recrystallization. This must often be a very gradual process, because the tubes of boring algæ which are commonly found traversing the substance of the coral are occasionally preserved after recrystallization. It will be noticed that the "mud" within the coral cavity has shared in the recrystallization, and now consists of a mosaic of muddy crystals. The form of these crystals is

probably rhombohedral, but their mutual interference during growth has prevented them from showing their characteristic shape. Many of the calcite crystals have dark muddy centers, a feature which is quite commonly met with in dolomite, but occurs very rarely in calcite. The type of alteration just described is not peculiar to corals, but is shared by all the aragonite organisms occurring in the coral rocks. Figure 5 from Mango, at a height of 370 feet, is an example of a fragmental rock which has suffered such a change.

FIG. 6.

MAKATEA, 150–175 feet. The matrix of the rock consists of partially recrystallized "mud." The cavities are lined with large scalenohedral crystals of calcite, many of which are very clearly zoned. × 80.

The matrix was originally "mud," but has now in part been changed to definite crystals of calcite.

Most of the aragonite organisms such as corals, some molluscan shells, tunicate spicules, and Halimeda have also been recrystallized, the original borders of such as were present being represented by dirt lines. It will be seen that organisms such as Lithothamnion and echinid spines, whose skeletons consist of calcite, show no tendency to change, and for the most part are quite unaltered.

Although when calcite is formed, it is most commonly found to crystal-

lize in rhombohedral crystals, yet occasionally a rock is met with in which the crystals are much more acute and consist probably of scalenohedra. This is more particularly true when the crystals are deposited from solution and line and project into cavities in the rock. This type of crystallization is seen in Figure 6, which represents a limestone from the central depression of Makatea.

The ground mass of the rock consists of "mud," some of which has been partially clarified in the process of recrystallization. The large cavity is seen to be lined with scalenohedral crystals of calcite, whose acute terminations project into the center of the cavity. One interesting and uncommon feature of these crystals is the marked zoning seen in many of them. This is probably due to the invasion of mud during crystallization, and while not uncommon in calcite from mineral veins is very rarely met with in crystals seen in sections of limestones. The above changes represent the normal structural and mineralogical alterations observed in these rocks, but there occur occasionally certain apparently anomalous features in the limestones. It has been noticed above that "mud" filling cavities in corals under certain conditions is converted into aragonite, but usually into calcite.

This is certainly true, but it is often noticed that the "mud" in a rock resists change after most of the organisms have recrystallized to calcite and even after another alteration, presently to be described, has still further obliterated the organic structure of the rocks. Where, however, the "mud" or other matrix in a rock becomes recrystallized it does not always happen that the organisms are also similarly altered at the same time. On the contrary, it has been occasionally noticed that the "mud" filling the cavities of a coral has become crystalline calcite, while the original aragonitic stereoplasm of the coral has broken down into a gray structureless "silt."

Many limestones, owing to the percolation of water containing carbon dioxide and to other causes, have passed or may pass through a series of changes such as has been described above. Whether or no a particular limestone, either unaltered or recrystallized, will undergo an important modification of composition and structure about to be described depends upon certain circumstances in the history of the rock about which very little is known.

This change consists in the introduction of magnesium into the limestone, and the partial replacement of calcium by magnesium carbonate. This replacement may go on in a rock until the amount of magnesium carbonate reaches as much as 15 per cent, and yet no sign of any min-

eralogical change may be noticed. Since dolomite and calcite are regarded as not being strictly isomorphous, if the magnesium carbonate occurred in the crystalline matrix of the rock it would be expected that crystals of dolomite should make their appearance. No such crystals are ever seen. It may be that an isomorphous mixture of calcium carbonate with magnesium carbonate may be possible up to about 15 per cent of magnesium carbonate, but if introduced beyond that amount, the stable compound dolomite is formed. A somewhat

FIG. 7.

CHRISTMAS ISLAND. No. 800. The matrix of the rock consists of dolomitic crystals, while a cavity is filled with clear dolomite. Some of the organisms have been incrusted with scalenohedra, while dolomite crystals have invaded some of them from without, inwards. × 30.

analogous change is described by Mr. L. J. Spencer, in connection with mixtures of copper and silver iodides.[1] On the other hand, it may be that the magnesium carbonate may be present in some form or another in the organisms. Unfortunately these are usually too small to be isolated for analysis. In this connection it may be mentioned that Högbom [2] quotes a series of analyses of specimens of Lithothamnion in which magnesium carbonate has been found forming from 3 to 13

[1] Min. Mag., June, 1901, pp. 43–44. [2] N. Jahresbuch für Min., 1894, I., 262.

per cent of the skeleton of the organism. When the amount of magnesium carbonate in a limestone rises above about 15 per cent, crystals of dolomite begin to make their appearance, at first in the matrix. As the amount of magnesium carbonate increases, the crystals become more plentiful, until a point is reached at which most of the matrix has been changed from calcite to dolomite. Even at this stage it often happens that no alteration has taken place in the structure of the organisms. The next change noticed is seen in Figure 7, a dolomitic limestone from Phosphate Hill, Christmas Island.

The matrix of the rock is almost entirely dolomitic, as are the clear crystals filling a cavity in the rock; while many of the organisms are incrusted with scalenohedral crystals. Crystallization has started to invade the organisms, and rhombs of dolomite are penetrating Lithothamnion from without inwards. It seems possible that the organism has already quietly absorbed magnesium carbonate without loss of structure, and that the present change is one of recrystallization. Certainly in some cases Lithothamnion which under the low power appeared to be almost unaltered, was found on examination with the high power of the microscope to have its cells filled with minute rhombohedra of dolomite. In the figure it is seen that dolomite crystals have filled and disintegrated the walls of the tubules of a Halimeda, that many of the dolomite crystals have regular zones of dirt, but that an echinid spine and an Amphistegina as yet show no sign of dolomitization. The order of disappearance of the organisms under dolomitization is not an invariable one, but it is usually noticed that Halimeda, if not already disintegrated, is one of the first organisms to disappear, while Foraminifera such as Orbitolites and Carpenteria and the alcyonarian spicules often resist dolomitization much longer. Lithothamnion is somewhat capricious. J. Walther[1] quotes a deposit in the Bay of Naples, in which Lithothamnion has disintegrated and formed a structureless limestone. He thinks the necessary condition for this to occur is that the organism should be subjected to percolating water. The decomposition of the animal matter within the organism gives rise to carbon dioxide, which, dissolved in the water, attacks the skeleton of the organism and dissolves it partly away. There is no doubt that in these coral limestones sometimes Lithothamnion does lose its structure comparatively easily, but, as a rule, the conditions have been favorable to its preservation, and it is found to be one of the most persistent forms. Other forms which seem to be at least equally persistent are such

[1] Zeitsch. deutsch. Geol. Ges., 1885, Vol. XXXVII., p. 329.

Foraminifera as Amphistegina and Heterostegina and the echinid spines.

The last stage in the dolomitization of a limestone, originally crowded with organic fragments, consists in the extension of the invasion of the organisms by dolomite crystals and the ultimate destruction of all traces of their organic character. This results in the formation of a structureless dolomite consisting entirely of clear or muddily zoned crystals. It is often noticed that partly as a result of solution, partly of consolidation

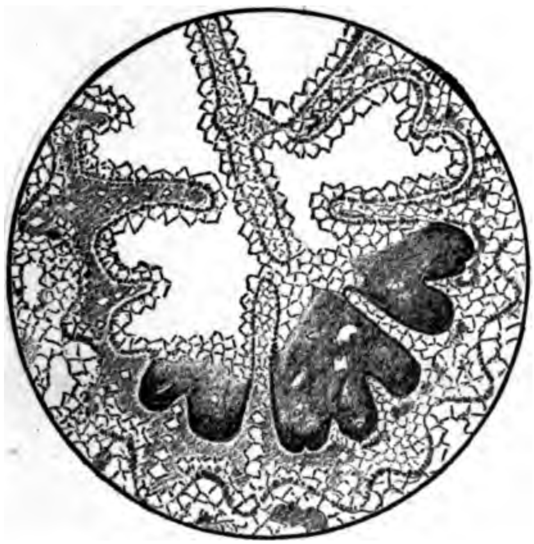


FIG. 8.

NGILLANGILLAH, 25 feet. Section of a dolomitized coral. The stereoplasm of the coral is now replaced by a dolomitic "silt," while the external and internal walls are represented by "dirt lines." Opaque "mud" in the cavities remains as calcite, and subsequent to its deposition, dolomite crystals, formed from solution, have incrusted the walls of the coral. × 30.

under recrystallization, the rock assumes a more or less cavernous appearance.

A somewhat parallel series of changes under dolomitization can be traced in the case of a coral section. Some of these changes can be seen on reference to Figure 8, which represents a section of reef-forming coral from the dolomitized island of Ngillangillah.

At a comparatively early stage in the history of the coral, some of its cavities were filled quite up to the wall of the coral with a dark "mud"

containing small fragments of organisms. Subsequently, dolomite crystals were deposited on the coral walls which can now be traced by a dirt line. The substance of the coral has been broken down, and its place is now taken by a fine gray dolomitic "silt," in which larger crystals of dolomite have formed. On applying Lemberg's test to a thin section of this rock, it is found that, in spite of dolomitization, most of the "mud" in the slide becomes stained, showing that it still consists of a finely divided calcite.

FIG. 9.

MANGO, 290 feet. A much altered cavernous dolomite, whose cavities are now nearly filled with large crystals of secondary calcite. $\times$ 30.

After the complete dolomitization of a rock, it is noticed that cavities are often filled or partly filled by the further deposition of crystals apparently from solution. This deposited material consists sometimes of dolomite, in which case the composition of the rock is not much changed; in most cases, however, the material deposited consists of broad crystals of calcite.

Figure 9 illustrates this point, and represents a section of a fragmental limestone from Mango at a height of 290 feet. The figure shows that the limestone has been thoroughly dolomitized, and as a consequence the organisms are largely obliterated, while cracks and cavities have arisen in

the rock. These have been subsequently filled with secondary calcite, forming broad slightly yellow crystals showing the characteristic cleavage, and ramifying into the cracks and cavities in the limestone. In this way the bulk analysis of a dolomitic limestone may be profoundly modified so that a dolomitic rock in which all organisms have been destroyed may, as a result of the infiltration of calcite, have its percentage of magnesium carbonate lowered from over forty to twenty or even under.

FIG. 10.

MANGO, 320 feet. (After staining with Lemberg's reagent.) A longitudinal section of a dolomitized coral. "Mud-floors" are seen partly filling cavities. Subsequently an incrusting layer of dolomite crystals was deposited, and finally many remaining cavities have been filled with secondary calcite which is now stained red. $\times 30$.

Figure 10, from Mango, at a height of 320 feet, shows how this change affects the appearance of a dolomitized coral. Some time before dolomitization started many of the cavities in the coral were filled up to a particular level by calcite mud slowly settling down from muddy water. The horizontality and general parallelism of these "mud floors" constitutes a marked feature in some longitudinal sections of reef-forming corals. It will be noticed that the "mud" extends quite up to the coral wall, showing that it reached its present position before the deposition of dolomite crystals began. Dolomitization subsequently invaded the sub-

stance of the coral, and crystals were deposited on the walls and on the surface of the "mud floors." Finally, many of the remaining spaces in the coral were filled with clear, slightly yellow crystals of calcite. On treating the section with Lemberg's solution, the secondary calcite is stained pink, while the mud in the cavities does not stain. Apparently during dolomitization, the calcite mud was quietly replaced by dolomite without any sign of recrystallization having taken place in the rock.

Two points of interest which arise in some dolomitic limestones remain to be recorded. It is well established that many dolomitized limestones consist entirely of rhombohedra of dolomite with dark, muddy-looking centers. As analyses of such rocks rarely show more than 40% of magnesium carbonate, it has been surmised that the muddy material in the centers of the crystals consisted of calcite. The author has demonstrated this to be the case in some sections of these rocks by treatment with Lemberg's solution when the muddy centers of the crystals become clearly stained by the reagent.

Finally it has been shown by the use of Lemberg's reagent on some of the rocks from Mango, that many quite colorless rhombohedra which appeared to be dolomite really consisted of alternate zones of calcite and dolomite apparently in optical continuity with each other. The author is not aware that this feature has been described before, and it appears to throw some light on a possible mode of formation of dolomite. This zoning may be explained in two ways.

It is possible that each crystal consisted originally entirely of calcite, and that alternate zones formed during the growth of the crystal possessed slightly different physical structures. When the rock was subjected to the conditions producing dolomitization, certain zones were converted into dolomite, while the rest of the crystal remained as calcite.

The alternative to this view is that the crystals originated in much the same way as artificially zoned crystals of alum are made. The crystal may have been originally dolomite or calcite, but from time to time the character of the solution in which the crystal formed changed in such a way as to determine the deposition alternately of dolomite and calcite *directly from solution*. The author believes this view to be more probable, and it seems to receive support both from the examination of the dolomite crystals found lining cavities in sections of some of the dolomitized limestones, and also from a macroscopic study of hand specimens which occasionally contain large cavities lined by concentric layers of incrusting dolomite crystals.

V. Conclusion.

In reviewing the facts which a chemical and microscopical examination of these coral limestones has elicited, it will only be possible at this stage of the inquiry to notice briefly three of the more prominent questions which arise. These are: — (A) The constitution and probable origin of the coral limestones, (B) their geological age, (C) the relation of the distribution of magnesium carbonate in the limestones to the question of the origin of dolomite.

A. The published accounts of the several islands, together with the detailed microscopical examination of the rocks, show that the limestones, apart from the bedded basal limestones dipping at 15°, are mainly of two types. True coral reefs occur here and there among the older rocks of the different islands, but are usually confined to the modern fringing reefs, which are now found on the slopes of the elevated islands, and were probably formed during pauses in the movement of upheaval.

The greater part of the masses of these upraised coral islands consists, however, of fragmental rocks, made up of pieces of reef-forming corals, together with the other organisms usually associated with corals in a reef. Globigerina and other deep-sea forms are found occasionally, but only in numbers approximating to those met with drifted into the lagoons of existing reefs. The evidence of the organisms as a whole, together with the intercalation of true reefs, shows that these fragmental deposits were laid down under shallow water conditions close to a true reef. The great thickness of these rocks may be accounted for in some cases by the outgrowth of a reef on its own talus during a period in which no vertical movement took place. Mr. E. C. Andrews is of the opinion that the bedded limestones dipping at 15° and interbedded with "soapstones," which form the basal rocks in the Fijis, were formed by subsidence, but that the unbedded limestones and reefs of later age were formed during intermittent periods of elevation, and form only a veneer of coral limestone, more or less perfectly masking the older bedded foraminiferal rocks.

B. The age of the older central limestones which form the greater part of the elevated coral islands has been determined with a fair degree of certainty in a few cases.

Prof. Rupert Jones and Mr. Frederick Chapman,[1] when examining the Foraminifera from Christmas Island, discovered in the oldest

[1] Monograph of Christmas Island, 1900, pp. 226–264.

limestone a form of Orbitoides, only known elsewhere from Oligocene and Eocene rocks, while higher up in the series other forms of the same genus occurred, which were correlated with certain forms found in Java, Sumatra, India, and other localities from rocks of Miocene age. The highest rocks of the plateau were doubtfully referred by Dr. C. W. Andrews to the Miocene on the report of Dr. Gregory on the fossil corals. Since the publication of the monograph on the Island, more sections have been cut, and I met with Orbitoides from two rocks collected near Phosphate Hill, so that the Miocene age of the rocks of the plateau is now fairly well established. The age of the inland cliffs and fringing reefs cannot be fixed with certainty. The Foraminifera, with the exception of rolled fragments of Orbitoides, all belong to forms still existing, but Dr. Andrews thinks that the upper inland cliff may be of lower Pliocene age, the lower inland cliff later Pliocene, while he assigns a Pleistocene age to the shore cliff. With regard to the rocks of the raised limestones of the Fijis, Tongas, etc., Mr. Agassiz maintains [1] that they consist mainly of Tertiary masses of limestone, an opinion largely based on their altered appearance and their relation to the undoubtedly more modern fringing reefs and terraces which occur on some of their slopes. I am able to confirm this opinion by fossil evidence from two of the islands of the Fiji group. In Mango a form of Orbitoides occurs at a level of 310 feet, which Mr. Frederick Chapman kindly identified for me as *Orbitoides sumatrensis*, a Miocene form from Christmas Island, Sumatra, and Borneo. The rock in which it occurs is, therefore, presumably of Miocene age.

One of the limestones from Namuka, another of the Fiji group, also contains a form of undoubted Orbitoides, which was, however, not capable of being specifically identified. It seems not unreasonable to suppose, that if more sections of these limestones were examined, the distribution of the genus Orbitoides over the islands in the Pacific would be still further enlarged.

C. The literature in relation to the question of dolomite is so large that it would be quite impossible within the limits of this present paper to discuss the subject adequately, but it may not be out of place to summarize a few of the more important opinions, which from time to time have been put forward by chemists and geologists in explanation of its formation. Gustav Bischof [2] gave an admirable account of the

[1] Bull. Mus. Comp. Zoöl., 1899, Vol. XXXIII., p. 10.

[2] Chem. and Phys. Geology, 1859.

results of the earlier workers on the question of dolomite, and made many experiments himself. He showed: —

(1) By dissolving mixtures of calcium and magnesium carbonates in water containing carbon dioxide, and then evaporating the solution at 122° F., that under these conditions the calcium carbonate was completely precipitated, while most of the magnesium carbonate remained in solution.

Hence dolomite could not be formed under ordinary conditions by the evaporation of water containing the two carbonates in solution.

(2) That the amount of carbon dioxide present in meteoric water sufficed for the production of a saturated solution of calcium carbonate.

(3) That in limestones containing magnesium, water saturated with carbon dioxide dissolved out only the calcium carbonate. Even when 11.5 % of magnesium carbonate was present only a trace of it was removed.

He quoted also examples of limestones containing up to 68 % of magnesium carbonate. In these cases the carbonates were not chemically combined, since dilute acetic acid dissolved out calcium carbonate alone. With true dolomite, the carbonates, when attacked, were dissolved out in molecular proportions.

The association of the dolomites of the Tyrol, with volcanic rocks rich in magnesia, led Von Buch [1] to suggest that the formation of dolomite was due to the eruption of volcanic rocks into a limestone, and that the change was brought about by the vapor of magnesium chloride.

Haidinger [2] attributed its formation to the action of magnesium sulphate on a limestone, under great heat and pressure.

Von Morlot [3] held a similar view to Haidinger, and by heating magnesium sulphate and calcium carbonate in a sealed tube to a temperature of 392° F., succeeded in forming a double carbonate.

Marignac [4] obtained a like result by substituting magnesium chloride for magnesium sulphate.

All these writers assumed that the formation of dolomite is connected with the intrusion of igneous rocks.

Later, Forchammer [5] suggested the reaction of spring-water, containing much calcium carbonate, with sea-water at a high temperature, as a possible cause of the precipitation of the double carbonate of calcium and magnesium.

[1] Ann. de Chim. et Phys., XXIII., p. 296.

[2] Poggend Annal., LXXIV., p. 591.

[3] N. Jahrb. für Min., 1847, p. 862.

[4] N. Jahrb. für Min., 1849, p. 742.

[5] Ann. de Chim. et de Phys. XXIII.

Prof. J. D. Dana,[1] after the discovery of magnesian limestone from the island of "Metia" (Makatea), advanced a theory of dolomitization, as applied to coral islands, which has been very largely accepted. He stated that the sea-water was the source of the magnesium, and that this is introduced during the consolidation of the limestone below the surface.

T. Sterry Hunt[2] stated two ways in which dolomite might be formed. The first consisted in the action of bicarbonate of lime upon solutions of magnesium sulphate, in which case gypsum was a subsidiary product. The second method was the reaction between river-water, containing sodiumb icarbonate, and sea-water in shallow basins, and the consequent decomposition of calcium chloride and magnesium sulphate into calcium magnesium carbonate, which, by subsequent heating, was converted into dolomite.

E. T. Hardman,[3] in his paper on the dolomites of the Carboniferous limestone of Ireland, contended that the alteration of Irish limestones to dolomite was due to the greater solubility of calcium carbonate in limestones containing some magnesium carbonate when acted on by water containing carbon dioxide in solution at atmospheric pressure. In support of this he quoted experiments he had performed on limestones containing some magnesium carbonate. He found, like Bischof, that under atmospheric pressure the calcium carbonate was dissolved and the magnesium carbonate was unaffected. Under high pressures magnesium carbonate alone was dissolved[4] from the mixed carbonates, and this method was formerly used commercially in the preparation of magnesium carbonate from dolomite.

In 1895 Klement[5] published a paper on the artificial formation of dolomite. He heated the finely powdered mineral or organism together with crystallized magnesium sulphate and a saturated solution of sodium chloride in a closed retort to a temperature of about 100° C. for two or three days. He then determined the percentage of magnesium carbonate in the washed precipitate. Under these conditions calcite took up only a trace, aragonite absorbed 34.6 per cent, while various corals yielded from 38.5 to 41.9 per cent of magnesium carbonate.

[1] Geology of United States Exploring Expedition, 1849, p. 153.

[2] Chemical and Geological Essays, p. 90.

[3] Proceedings Royal Irish Academy, 1877, pp. 705–730.

[4] Dingl. Polyt. Journ. CC. IX., p. 467; also Abs. Journ. Chem. Soc., Vol. XII., p. 96.

[5] Ueber die Bildung des Dolomit, Tscherm, Min. Pet. Mitt., 1895, XIV., p. 526.

In 1898 Mr. Stanley Gardiner[1] attributed the dolomitization of coral islands to the greater insolubility, in water containing carbon dioxide, of the double carbonate of calcium and magnesium over that of either calcium or magnesium alone. He believes this causes a concentration of the magnesium carbonate in certain limestones, and that this concentration may be aided at times by the evaporation of the spray from sea-water.

It is clear, in view of the distribution of dolomite in coral islands that the early views of Von Buch, Haidinger, Von Morlot, and Marignac are quite untenable if applied to the dolomitization of such structures. A study of the results of analyses from different localities shows that there is no necessary relation between dolomitization and the presence of volcanic rocks. Although Christmas Island, Mango, and other islands which are partly volcanic also contain dolomitic rocks, yet, in most cases, the volcanic rocks are immediately associated, not with dolomite but with a non-magnesian limestone. Again, no dolomitization has been discovered in the volcanic island of Guam. On the other hand, islands such as Vatu Vara and Ngillangillah, in which no volcanic rocks have been found, are dolomitized from top to bottom. The views of T. Sterry Hunt are open to several objections. The formation of gypsum, associated with dolomite, appears to militate against his first view, since gypsum has only been recorded from two or three coral islands, and never, so far as I am aware, in association with dolomite. The gypsum from raised atolls is, however, derived from sea-water by simple concentration, while that from the double decomposition of magnesium sulphate and calcium carbonate might be kept in solution in sea-water by means of its greater solubility (1 in 400) than that of dolomite. His second explanation involves the mixing of river-waters, containing sodium bicarbonate in solution, with sea-water, a condition which is not realized in the neighborhood of coral islands.

Hardman's views were advanced to explain the local dolomitization of the Carboniferous limestone of Ireland and could not apply to islands such as Vatu Vara and Ngillangillah where apparently the whole islands are dolomitized. At the end of his paper he remarks that it is probable that deposits like the magnesian limestone may be due to evaporation and assimilation of magnesium carbonate by animals in the lagoon and subsequent alteration to dolomite; and that only in this way could large masses of dolomite be formed. Stanley Gardiner's views appear to be very similar to Hardman's, and can only have a very local application. Most limestones contain not more than two or three per cent of mag-

[1] Proc. Camb. Phil. Soc., 1898, Vol. IX., Part VIII., pp. 417–503.

nesium carbonate, and consequently to form a dolomite from a rock of this character would require a very extensive solution and concentration of the original limestone. The experiments of Klement, in 1895, demonstrated that the unstable mineral aragonite is much more susceptible of the invasion of magnesium carbonate than the stable form calcite. The conditions under which the experiments were performed make a strict comparison with reef dolomitization difficult. The results are, however, very suggestive as showing that magnesium sulphate can, under certain conditions, react with calcium carbonate. The stable compound calcium magnesium carbonate is deposited, while the by-product calcium sulphate can be kept in solution by dilution. It may be that the reaction which proceeds quickly under conditions of great concentration and high temperature may proceed slowly, but no less surely, in superficial waters such as those of a lagoon which is maintained for a sufficiently long period of time under uniform conditions.

Recently it has been suggested that the introduction of magnesium into a coral limestone is only effected when the rock has been submerged for some time to a considerable depth corresponding to a particular pressure. This view is, however, not in harmony with the facts at Christmas Island, Mango, Vatu Vara, Ngillangillah, etc., where the highest rocks of the island are dolomitized, and the only movement of which there is evidence since their formation in shallow water is one of elevation. It is true that denudation has removed a certain thickness of rock since their elevation, but there is evidence that in the islands mentioned the effects of denudation have not been extensive.

It will be seen that most of the opinions which have been put forward to explain the introduction of magnesium carbonate into coral rocks do not agree with the facts herein recorded as to the distribution of dolomite in upraised coral islands. There yet remains Dana's well-known theory of dolomitization, and perhaps some modification of it will be found to harmonize more closely with the evidence than any view which has, as yet, been put before geologists. The occurrence of dolomite at the summits of many of the islands is significant. At Christmas Island dolomite is found near the summits of the highest hills immediately below beds of phosphate. Dr. C. W. Andrews believes that after Miocene times the movement of subsidence to which the formation of the older limestone is due, ceased, and a very long period of rest ensued, during which the only land masses rising above the lagoon were the low islets now forming Murray, Ross, and Phosphate Hills. The accumulation of guano from the droppings of sea birds, and its subsequent altera-

tion of the limestone by percolating water, formed the beds of phosphate now found capping these hills. The occurrence of beds of dolomite immediately below the phosphate seems to point to its *formation in waters near the surface*, possibly those of the lagoon. The occurrence of dolomitic rocks from the inland cliffs and terraces of Christmas Island and Eua seems to support this view, although these dolomitic limestones may be derived from the débris of the older rocks of the central nucleus of these islands. Mr. E. C. Andrews states, however, that the lower dolomitic limestones of Ngillangillah are from a fringing reef. This view is supported by the fact that the upper raised fringing reefs in the Red Sea are dolomitized.[1] It seems probable that the introduction of magnesium into the limestones does take place from the waters of the lagoon under certain favorable conditions. What these conditions are it is at present impossible to say with any degree of certainty. It is improbable that concentration to any marked extent can take place in lagoons unless they are entirely shut off from the sea. Before this question can be attacked successfully much fuller information must be obtained as to the chemical composition of lagoon muds, and analyses must be made of the waters of lagoons and those of the open ocean outside coral islands. It may be that the carbon dioxide liberated on the death and decay of both plants and animals helps to dissolve their calcium carbonate, which under these conditions may react with magnesium sulphate of the sea-water, and precipitate the insoluble double carbonate of calcium and magnesium, while the more soluble calcium sulphate, formed as a result of the reaction, could remain in solution. Whatever the conditions for the introduction of magnesium carbonate into coral limestone may be, it seems probable, from the distribution of magnesium carbonate in upraised coral islands, that the introduction takes place at or near the surface of the water, and that a limestone exposed to suitable conditions for a sufficiently long time will become dolomitic. The occurrence of dolomitic limestones at several horizons in an island might be accounted for either on the theory of subsidence or of elevation, by changes in the rate of movement of depression or upheaval. An ordinary non-magnesian limestone might result from a somewhat rapid subsidence or elevation, while a constant and slow subsidence or upheaval might result in the formation of a completely dolomitized island. The extent to which a rock will become dolomitic must depend largely on the dura-

[1] Walther, J. Abhandl. math. phys. Königl. Sachs. Gesellschaft der Wissenschaften Bd. xiv. p. 494, Hume, Rift Valleys of E. Sinai. Int. Geol. Cong. Paris, 1900, pp. 32–40.

tion of the exposure of the limestones to the conditions producing dolomitization.

In conclusion it must be stated that this paper is necessarily incomplete, and is only intended as a first contribution towards the chemical and microscopical examination of upraised coral islands. It is hoped, however, that the results which have been obtained may not be without interest to geologists, and that some of the facts may help to throw light on the fascinating problems which have for so long been associated with coral reefs.

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Historical Statement. — The larger mountain ranges of the Great Basin offer problems of especial interest, inasmuch as the faulting by which their present relief is believed to have been produced is not proved by stratigraphic evidence of the kind familiar to geologists, but by physiographic evidence of a kind to which little attention is usually given. These ranges were described by King in 1870 as "ordinarily the tops of folds whose deep synclinal valleys are filled with Tertiary and Quaternary detritus" (a, 451). Soon afterwards Gilbert concluded that the individual ranges were the carved upper parts of tilted or lifted blocks, resulting from "the displacement of comparatively rigid bodies of strata by vertical or nearly vertical faults" (1874, a, 50). The same view was elaborated in a later report (1875, b, 21–42). Powell, Dutton, and Russell adopted essentially the same explanation. King also seems to have recognized the validity of Gilbert's conclusion, for in 1878 he modified his earlier views by recognizing frequent faulting at a later date than that of the folding by which the great anticlinals and synclinals had been produced (b, 735). None of these observers, however, gave explicit consideration to the three elements necessarily involved in the problem of block faulting; namely, the prefaulting topography, the topographic effect of the faulting, and the work of erosion on the faulted blocks.

The latest general discussion of the region is by Spurr, in whose essay a review of earlier writings may be found. This author concludes that "the mountain fronts studied are, in general, not marked by great faults, and, conversely, that the ascertainable faults are very rarely attended by simple fault scarps." He therefore rejects Gilbert's hypothesis and explains the Basin ranges as the "results of compound erosion active since Jurassic times, operating on rocks upheaved by compound earth movements which have been probably also continuous during the same period." It is further suggested that the ranges were probably differentiated during Cretaceous time, when a greater precipitation is assumed to account for their dissection: "subsequently the climate became arid and the water supply was not sufficient to remove the detritus from the valleys, which filled up" (1901, 265, 266). I have elsewhere briefly stated the reasons why this explanation seems unsatisfactory (1901, a).

The Basin ranges have for some years been of special interest in systematic physiography, for if Gilbert's explanation of them is correct, they offer unusually simple examples of mountain uplift and sculpture; examples that may be adduced as relatively elementary illustrations of the difficult group of mountains in general, and that may therefore be with propriety presented to beginners for introductory practice before the description of complicated mountain ranges is undertaken. This opinion was confirmed on the appearance in 1884 of Russell's vivid account of the faulted lava-block ranges of southern Oregon; for these seemed to be even simpler and younger than the ranges farther south. Ranges of this kind are of a further interest in that they support in a certain measure the more primitive theory of mountain-making; namely, that mountains are the immediate results of uplift, comparatively little modified by erosion, while the intermediate troughs are the effects of depression: in a word, that dislocations of the earth's crust are here chiefly responsible for the observed relief of the region, and that the part played by erosion is subordinate. It is now generally agreed that this primitive theory finds little support in such ranges as the Alps, where the existing forms of peak and pass, spur and valley, are the product of extensive erosion in a deformed and broadly uplifted mass. A recurrence to the older theory in explanation of the ranges of the Great Basin is therefore a wholesome discipline.

It has for some time seemed to me that there was good evidence for regarding the Oregon lava-block ranges as types of the youngest, most elementary mountain forms known to geographers, and for placing the ranges of the Great Basin in Utah and Nevada as types of larger and more maturely sculptured ranges, appropriately following the introduc-

tory examples of southern Oregon. In view of this relation of the Basin ranges to the problems of systematic physiography, the opportunity of seeing some of them last summer was especially welcome, even though the time that could be given to them was brief. The conclusion reached was that faulting has recently exercised and indeed still exercises a dominant control over the uplift of all the larger mountain ranges observed, but that erosion has greatly modified the form which would be produced by faulting alone, and that the prefaulting form is for this reason generally not recognizable.

Theoretical Considerations. — It seems desirable to present the observations that have led to this conclusion in an order that is suggested by a deductive consideration of the problem, such as is necessarily entertained in the establishment of ideal physiographic types of mountain forms. In this way the complete ideal types of carved block mountains may be first carefully conceived and visualized in the imagination, all their essential features being systematically developed. The observed elements of form may then be described in their proper relation to the whole of which they are believed to be but parts.

The various types thus conceived in the imagination must represent all the hypotheses by which the facts in hand may be explained, the advantages that follow from a due consideration of "multiple-working hypotheses" having been convincingly set forth by Chamberlin. In publication, however, it is permissible to give relatively little space to those hypotheses which have been proved incompetent during the progress of an investigation, and to set forth in detail only the one which has gained — in the author's opinion at least — the rank of a successful theory. For this reason, the following pages are chiefly devoted to a consideration of the Basin ranges as dissected fault-block mountains.

The author feels that some apology is needed for his writing on a field where his own observations are very limited in comparison to those of others who have a much wider experience in the Cordilleran region. His reason for adding yet another essay to the already abundant literature on the mountain ranges of the Great Basin is chiefly that the articles thus far published have not included a detailed analysis of the problem in hand, and in particular that the effects of erosion upon the faulted mountain blocks have received but little consideration. Gilbert's brief statement, written thirty years ago as the result of his first western expeditions in 1871, 1872, and 1873 (b, 40, 41), is hardly more than a summary of conclusions. Russell explains the Basin ranges as having been "formed by the orographic tilting of blocks that are separated by pro-

found faults" (a, 8), and leaves the erosion that they have suffered to be inferred. Elsewhere, when describing the West Humboldt range, he says: "The precipitous mountain face . . . is in reality an ancient fault scarp of grand proportions, which was somewhat eroded before the existence of Lake Lahontan" (a, 277); but "somewhat eroded" does scanty justice to the fine sculpturing of this range as shown in the accompanying Plate XLV. Spurr distinguishes between scarps directly due to faulting, and scarps due to the erosion of a long-ago faulted mass; but he gives no explicit discussion of the forms assumed by a simple fault scarp as it undergoes dissection; and his attention to the physiographic features of the Basin ranges in general is so brief that he implies that they possess an intimate correlation of structure and form by saying that the Appalachians "likewise consist of parallel ridges eroded along lines of folding" (255).

In spite therefore of the many descriptions of the Basin ranges that have been published, there has not yet appeared any detailed statement of the theory by which they are explained; the essential consequences of the theory have not been explicitly formulated; the criteria by which a fault-block mountain may be recognized in early or later stages of dissection have not been defined; and it is to supply these deficiencies that the preparation of this essay was undertaken.

When the essay had reached an almost completed form, the writer had the advantage of hearing the Basin range problem discussed by Mr. Gilbert at the Washington meeting of the Geological Society of America, in January, 1903. It was a gratification to find that the plan of presentation here adopted very closely resembled in various ways the treatment offered by the originator of the Basin range theory: it was at the same time an embarrassment to see that many of these pages would be hardly more than repetitions of Mr. Gilbert's report. They may, however, have a certain value in so far as they show that independent study leads to accordant results.

Ideal Types of Fault-block Mountains. — There are two chief types of fault-block mountains as illustrated in Figures 1 and 2: one shows what may be called a tilted block, the other a lifted block. In order to economize space, only the tilted block type will be here considered in detail.

The most characteristic features of a typical tilted block mountain in its youth or early maturity may be summarized in Figure 1 in which the block, ACE, has been raised and more or less inclined. The upper part, BC, of the faulted face, AC, rises above a piedmont plain of waste, BD, by which the backward slope of an adjoining block is buried; while the

backward slope of the block, CE, is also partly buried in a plain of waste, FJ, which meets another waste plain from a third faulted block, EK.

Certain features shown in the figure are essential to the type in the stage of erosion here considered. The fault-bounded block, ACE, must present a back-sloping surface, CFE, whose form before the faulting occurred is now more or less modified by erosion in its exposed part, CF, and buried under waste in its depressed part, ~~AB.~~ FE The lower part, AB, of the faulted face, ABC, is buried under the waste derived from the exposed and more or less dissected part, BC. Blocks which stand so high that the trough between them is now dissected instead of aggraded

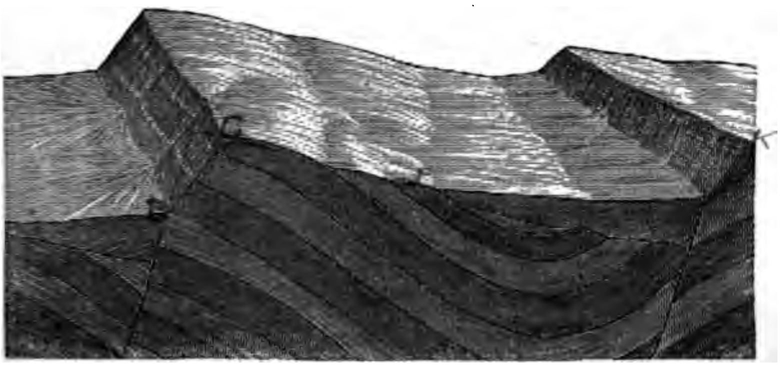

FIGURE 1.

Diagram of a tilted block; youthful stage.

are not here considered. Examples of this kind are described in the northern Sierra Nevada by Diller (1886, 12–16).

Other features of the type are extremely variable. The size, structure, and form of the block are entirely undefined. Its upper surface may have been in the prefaulting period, a peneplain worn down on ancient schists; a mountain area of folded or faulted strata more or less subdued by erosion; a series of horizontal and slightly dissected aqueous or igneous strata; or anything else. The block faulting may be on a large or small pattern; of regular or irregular arrangement; reaching over an extensive or a restricted area; of great or little displacement; and with much or little tilting.

The displacement may be slow or rapid, uniform or variable in rate, of brief duration or long continued, of remote or recent beginning and ending; it may vary greatly in amount along the fault line, diminishing

How many, who have not studied Paleontology, know what the "septa of an ammonite" look like?

to its end; as faulting continues, the length of the block may increase, and its end will thus vary in position. The faults may be simple or complex; the faulted front of a block may be clean cut, stepped, or shattered; the fault line along the mountain base may be essentially indifferent to the structure of the block, for the fault may be of deep-seated origin and not necessarily guided by the pre-existent foliation, stratification, folding, or faulting that is seen in the upper part of the block. The fault surface may be nearly a plane or a conspicuously curved surface, but from all that is known of faults it cannot possess sharp or exaggerated irregularities such as are seen in the septa of an ammonite. The uplift and tilting may vary widely in the different examples of a single district. Appro-

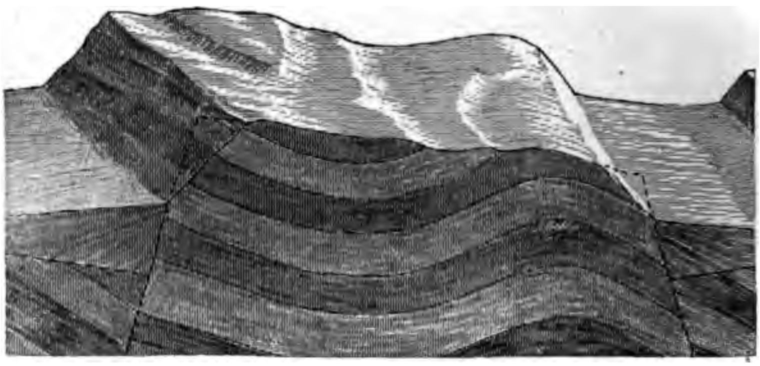

FIGURE 2.

Diagram of a lifted block; youthful stage.

priate to all these variable elements, the present form of a faulted block may exhibit little or much modification by erosion; little modification being consistent with rapid and recent faulting of a resistant block in very arid climate; much modification being consistent with slow and ancient faulting of a weak block in a climate of sufficient rainfall to produce active erosion. In a block whose length has been increasing during a long time of increasing displacement, it would be reasonable to expect a mature dissection near the middle of the block to give way to young dissection near the ends of the block; for the middle part will have been long exposed to erosion while the ends will have been but lately uplifted. The prefaulting form of the block surface will usually be longest preserved near the base of its exposed back slope, CD, and the form due immediately to faulting will be best seen near the base of the front, CB.

As long as the faulting and tilting continue, strong relief may be maintained; but after displacement ceases, erosion will advance without more hindrance than is offered by the resistance of the rocks; it will slowly subdue the earlier relief to rounded forms, and still more slowly widen the valleys and consume the intervening hills as the forms of old age, Figure 3, are realized. In a late stage of degradation, the mountain mass will be invaded by numerous flat-floored, branching valleys between low, rounded forking spurs. The valleys will then be largely adjusted to the weaker rock structures, while the fading ridges will stand longest where upheld by the resistant structures. The mountain base, an

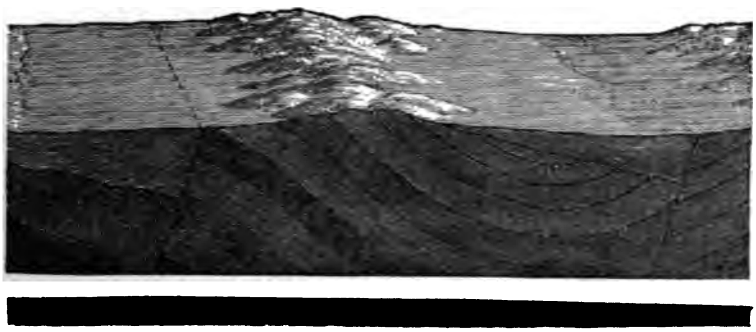

FIGURE 3.

Diagram of a tilted block; old stage.

irregular line, will have no close relation to the path of the fault, and the slope between the mountain base and the fault line will carry a thin and discontinuous veneer of waste on a planed rock floor. It would probably be impossible to distinguish the residuals of tilted and lifted blocks in a late stage of erosion.

Place and Value of Deduction. — It is important here to emphasize two general considerations. First, the details of form appropriate to any desired special case under the ideal type should be deduced with as much completeness and definiteness as possible. As long as the details of a theoretical form are vaguely conceived, the observer will be unable to give his theory a rigorous test; its consequences will be so indefinite that he can hardly say whether they are confirmed or contradicted when he confronts them with the appropriate facts of observation. It is particularly important that deduction should not be postponed till after the field work is "completed" and after the field is left. The two processes

of observation and deduction should go on together in the field, each aiding the other, if the investigator would avoid as far as possible the disappointment of finding afterwards that the field records are deficient in some particular point where fuller record would have been of critical value in testing a deduction. Memory may sometime supplement written record, but it is notoriously dangerous to trust to unwritten notes. In my own experience, however, careful deduction is more difficult than observation in the field, but it is greatly aided by deliberate thinking and writing while the facts are before the eyes.

Second, it must not be assumed that a theory gains support because its consequences can be definitely deduced. However accurately one may argue out the details of form appropriate to a certain stage in the dissection of a faulted mountain block, the theory of block faulting becomes a demonstrated occurrence only when the sharply deduced consequences of the theory are shown to accord with closely determined facts of observation.

Not only is it important that an investigation should give equal attention to deduction and induction; it is essential to clear presentation that both phases of inquiry should be sufficiently published. It is otherwise almost impossible for the reader to discriminate between sound and unsound conclusions. It is conceivable that an able observer should patiently collect and record a multitude of facts, and that he should very imperfectly set forth the reasons that lead him to the announced explanation of the facts. The hurried reader may in such a case quote the announced explanation and accept it, if he wishes, on the authority of the writer; but the more critical reader will wish to make his own measure of the validity of the announced conclusion, and this he will find difficult in the absence of explicit announcement of the method of reaching it. It is particularly important to consider the deductive side of any problem in which there is substantial agreement among different observers as to the facts directly observable, but in which there is difference of opinion as to the explanation of the facts; for in such a case the correct solution of the problem turns essentially on the validity of the deductions by which the unobservable facts of the past are brought into mental vision.

It may not be amiss to point out that the investigator's effort in all such problems as the one here in hand is simply to supplement the directly observable present facts by the discovery of the unobservable past facts, so that the entire phenomenon shall become known. If observers of sufficient penetration had been present in the Great Basin during all

the formative period of each mountain range now seen, their records of unobserved fact might give a complete account of all the processes involved; and it would then be perfectly clear whether the mountain ranges were carved fault blocks or not. In the necessary absence of such observers, we try to replace their records by our discoveries, and although our method of discovery necessarily has recourse to the imagination, the phenomena that we successfully discover are facts of only a slightly different order from those of direct observation. We see certain forms imprinted in stratified rocks, and by reasonable mental process arrive at the conclusion that these are the remains of once living organisms. We see two groups of similar strata in similar sequence, and by reasonable mental process reach the belief that their present discontinuity is the result of what is called faulting. In both these cases, the inferred explanation is accepted by most geologists as of essentially the same order of verity as the observed fact, because it has now stood the test of repeated and minute scrutiny. In the case of the Basin ranges, interpreted as carved fault blocks, many geologists are at present by no means disposed to attach equal value to the existing facts of structure and form reached by direct observation and the supposed past facts of dislocation reached by mental inference. It is therefore appropriate that special attention should be here given to the method of inference by which the past facts are resurrected.

It is the application of the combined inductive and deductive method here sketched, although always applied less consciously and completely in the field than could be wished, that has satisfied me of the essential correctness of the theory which explains the larger ranges of the Great Basin as well-dissected blocks of long-maintained faulting, continued into recent time.

Evidence of Faulting along the Mountain Base. — The first elements for consideration in this problem are those which should, in a type example of a long-faulted, well-dissected mountain block, be expectably associated with the occurrence of a fault along the mountain base.

The simplest and most manifest element of this kind is a nearly straight or but moderately curved base line, Figure 1, passing indifferently across or obliquely along the structure of the mountain mass which rises rather abruptly and continuously on one side, while a sloping plain of waste is spread out on the other. The simple continuity of the base line and the complete absence of rock outcrops on one side of it are essential consequences of long-continued block faulting, and are at the same time not characteristic of any other available geological process. As Emmons

wrote nearly thirty years ago, one cannot "imagine an erosion which would leave an abrupt wall of 7,500 feet in height on one side of a valley nearly twenty miles wide" (345). Hence wherever these theoretical consequences are borne out by facts of direct observation, block faulting is thereby given so high a degree of probability while other processes are rendered so highly improbable that the theory of block faulting may be looked upon as well introduced, at least.

The best examples that came under my observation of actual forms which match these preliminary members of the whole series of deduced type forms were not among the Basin ranges proper, but along the bordering Wahsatch mountain front, by which the Great Basin is limited on the east. The mountain base near Provo and near Ogden deserves careful study in this respect.

The Wahsatch range is divided into several local mountain groups by the canyons of streams that rise a number of miles east of the line of higher summits and flow westward to Salt Lake Basin. In the neighborhood of Provo, the canyons are those of Spanish fork, Hobble creek, and Provo river, between which the mountain groups may be called the Spanish peaks, Wahsatch, and the Provo peaks Wahsatch, or more briefly the Spanish and the Provo Wahsatch (Emmons, 340, 344).

Close by Provo, where my party had the most leisure for attention to this problem and where we had the advantage of guidance by Prof. E. H. Hinckley of the Academy in that city, the expectations of theory are extraordinarily well supported by the facts. The mountains spring boldly from the plain; their base line breaks obliquely across the tilted and folded rocks of the mountain mass: the occurrence of a base-line fault is explicitly stated by Emmons (345). Views of the Provo Wahsatch from the roof of the Academy in Provo looking northeast and southeast are given in Plate **4**. We made an excursion up Rock canyon, Plate **4**, A, to a mid-monoclinal ridge back of the frontal summits, and returned by Slate canyon, Plate **4**, B. There are some indications of faults in the longitudinal valleys between the monoclinal ridges (Emmons, 345, 348), but nothing at present known serves to give date to these faults, should they be proved to occur. Figure 4 shows the generalized structure thus determined: an anticlinal axis lies near the western base of the mountains opposite Provo, while a great monocline, the eastern half of the incomplete anticline, constitutes the rest of the range. Further south, the anticline is not seen at the mountain base. The rocks in the anticlinal axis are said to be mid-Palæozoic; those of the crests are Carboniferous (Emmons, 345,

346); further east the maps of the 40th Parallel survey indicate Mesozoic strata. West of the mountain base, no rocks are seen in place; the gravel beaches and deltas of Lake Bonneville descend to the alluvial plain that slopes under the shallow waters of Utah lake.

About twelve miles southeast of Provo, the Spanish Wahsatch, lying next north of Spanish fork canyon, is even more emphatic in its testimony for block faulting. A view along its base is given in Plate 1, B. Its rock layers are nearly horizontal or dip gently eastward. Some significant details of its form will be considered later.

The Wahsatch near and northwest of Ogden presents several significant features, even when seen only from a railroad train. Its base line is here of moderate curvature, and manifestly traverses various structures, as indicated both by form and by color. The mountain front rises abruptly and continuously from the base line, except for brief interruptions in narrow-mouthed canyons.

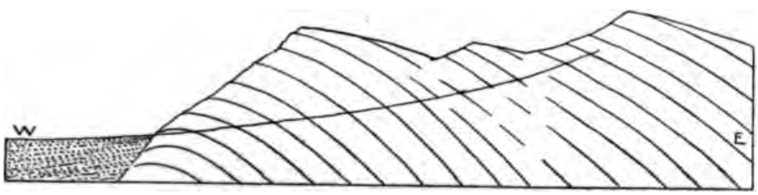

FIGURE 4.

Rough cross-section of the Provo Wahsatch, looking north.

The features of this range and of several others further west, as seen from the passing train, were so accordant with the features more deliberately observed near Provo that the burden of proof seems to me to rest with those who regard the ranges as other than carved fault blocks; but while observations from a train may have a high value to the observer, I am well aware that they will not be regarded as convincing by others, especially not by those whose habitual work in palæontology, petrography, or minute stratigraphy has given them no acquaintance with the value of large elements of form in physiographic problems, even though these elements be only hastily observed from a car window.

During a stage ride northward from Winnemucca, Nev., into southern Oregon, I passed the Santa Rosa and Pine Forest ranges, both of which exhibited very clearly the gently curving base line, regardless of rock structure, and the bold mountain front, continuous except for sharp-cut canyons, that are essentially characteristic of carved-block mountains.

The western face of Jackson range near its northern end had the same appearance, but this was very imperfectly seen. Further details concerning the first two of these ranges are given in a later section. Examples of sloping waste plains in front of dissected ranges are given in Plate 2, while the linear front of the Pueblo range is illustrated in Plate 3, A.

The Base Line of Residual Mountains. — It may be worth while to state at this stage of the discussion the reasons for rejecting the theory that the mountain ranges just described are the residuals of much larger masses, of which the vanished parts have been removed by erosion. These reasons are found, not at all in the incompetence of erosion to wear away mountains, but in the impossibility of explaining the forms of the mountain ranges above-named as the residuals of much larger masses. There are numerous examples in which the general subaerial erosion has sufficed to remove mountains more or less completely, but no examples in which the residuals of half-consumed mountains exhibit the features above described as characteristic of certain Basin ranges. Several special cases may be considered.

The only residual mountains known to physiographers as having a relatively continuous mass and rectilinear base are those in which structure controls form, as in the stratified Appalachians of Pennsylvania and Virginia. There the ridges of resistant sandstone rise between rolling lowlands of weaker strata; the ridges are occasionally cut through in water gaps, but between the gaps they frequently present a continuous mass sloping evenly to a nearly rectilinear base. When the strata bend, the ridges turn: when the strata are cut off by a fault, the ridges end. Structure is perfectly expressed in form. The same rule applies to the trap ridges of the Triassic areas of Connecticut, New Jersey, and Pennsylvania; but the rule clearly enough does not apply to the Wahsatch mountains and the other Basin ranges above named.

Residual mountains whose survival is not dependent on contrasts of rock resistance so striking as those of the Appalachians, and whose structure is relatively massive, are well illustrated in the crystalline Appalachians of North Carolina and Georgia. In mountains so old as these, it is to be presumed that the valleys have generally come, by a process of long-sought adjustment, to follow the somewhat weaker rocks, while the mountains represent the more resistant masses. None of these mountains, however, have a bold descent to a nearly rectilinear base; all of them give forth spurs which as a rule slope more and more gradually as they fade away on the valley lowlands; while branch valleys enter between the spurs far into mountains. The mountain base line is sinuous and ill-defined.

One of the most remarkable of these many residuals is a group of radiating spurs that culminate in Big Bald mountain in the older Appalachians of northern Georgia (Ellijay map sheet). The spurs have a notably stellate arrangement between open centrifugal valleys, showing that the mountain is to-day the mere skeleton of a once much larger body; its emaciated form is highly suggestive of the gnawing erosion which it has so long suffered.

A good example for contrast with the Basin ranges is found in the strong east-facing escarpment known in northern North Carolina and

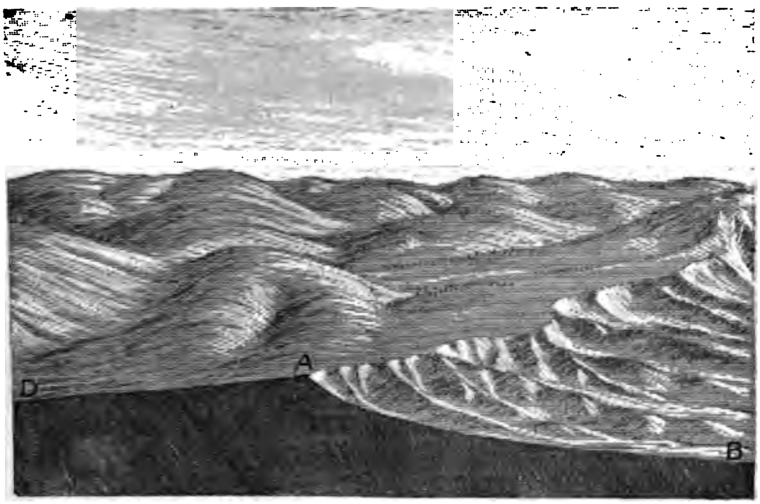

FIGURE 5.

Diagram of the Blue Ridge escarpment, North Carolina, looking north.

southern Virginia as the "Blue Ridge." The escarpment, AB, Figure 5, is evidently retreating westward, for it is simply the headwater slope of the short-course Atlantic rivers, which are actively capturing drainage area from the higher-lying headwaters, AD, of the much longer rivers of the Mississippi system. Viewed in a very general way, as on a small scale map, the base of the scarp is of moderate curvature, and its slope is essentially independent of structure; hence in both these general features it might be said to resemble the face of a Basin range. But when viewed in detail, the base of the escarpment is sinuous in a high degree, with numerous branching spurs that advance between well-carved amphitheaters; the spurs gradually fade out forward, instead of

being abruptly terminated at a well-defined base line, as is so persistently the case with the above-described ranges of Utah and Nevada. In some cases the spurs run far forward, forming ridges of undulating outline by which embayments of the piedmont lowland are divided. The contrast of the Blue Ridge escarpment and the Basin ranges is therefore extremely instructive. The topographical maps of the North Carolina mountains are worth examining in this connection: Wilkesboro, Cranberry, Mt. Mitchell, and Pisgah (N. C.), and Hillsville (Va.) sheets afford the best illustrations. Some account of their peculiar features is given in a recent essay by the author (1903).

The only conditions under which residual mountains have a well-defined, moderately curved base line is where they are cut across by a master river, or laterally attacked by the waves of a vigorous sea; but these conditions are so manifestly inapplicable to the region of the Basin ranges that they need no consideration here, except in so far as they suggest that a trenchant cause is needed to explain the well-defined base line to which the ranges descend.

Residual Mountains in the Great Basin. — There are, however, some excellent examples of residual mountains among the Basin ranges. Those that I saw are of much less height than the ranges thus far described. Their forms are thoroughly subdued. They have no well-defined and moderately curved base line, but descend in branching, sprawling, fading spurs, which interlock with broad, flat-floored, branching valleys. The contrast of these nearly worn out mountains with the more vigorous forms previously considered is most striking, yet it is entirely conceivable that the contrast may be due simply to stage of development and not to difference of origin. It has already been shown that the late stage of dissection of a fault-block mountain would, long after faulting had ceased, present essentially such worn-out forms as are here described, for the sharp definition of the base line would be lost after faulting had weakened and stopped. On the other hand, the old residuals of massive mountains of any other kind would also present these worn-out sprawling forms. There are indeed no tests by which the two kinds of old mountains can be easily distinguished.

Several examples of residual ranges in the Great Basin were noted as follows: North of Tecoma, Central Pacific railroad, there are mountains of moderate relief, whose rounded branching spurs descend gradually to low, sprawling, dwindling terminals, between wide-open, waste-floored valleys. The fading spurs and open valleys interlock on a very sinuous line. These well-defined features gain an added value by their

contrast with the Ombe and Ute ranges, south and west of Tecoma: both of these are of strong relief, with relatively rectilinear base lines on the sides toward the railroad. Their valleys are steep-sided and narrow-floored, causing but little interruption in the otherwise continuous mountain front. Nevertheless, these higher ranges have been abundantly carved, so that their peaks and spurs preserve no indication of an original block form; and no signs of modern faulting, elsewhere so easily recognizable from the train, were here visible.

North of Omar, there is a typical subdued mountain mass, whose dwindling spurs interlock with open valleys. This example was strongly contrasted with the lofty Humboldt range, south of Wells; here the snow-patched peaks descended by strong slopes to a relatively rectilinear base line on the northwest.

Northeast of Golconda, Nevada, a low range descends to a very ragged base, one of the best examples of the kind that my trip discovered. Its description would involve a repetition of what has just been said for other similar ranges, though the description here might be somewhat more emphatic than before.

The only example of this class which I photographed was a small unnamed range, about forty miles north of St. George, Utah, here reproduced in Plate 7, B. Its spurs were long drawn out, with concave profiles toward their base; its valley mouths were wide open, holding broad waste-covered slopes. Its base line was sinuous and indefinite, in the strongest contrast to the simple and definite base line of the Spanish Wahsatch, Plate 1, B.

The Cañyons and Ravines of Block Mountains. — If we now return to the consideration of the higher Basin ranges, it seems undeniable that faulting gives a much better explanation of their base line than can possibly be given by erosion. Indeed, erosion can be appealed to for the removal of the missing mountain masses only so long as the processes and results of erosion are looked upon as arbitrary and beyond reduction to those generalizations known as natural laws. The day has passed when this is permissible. Erosion, whether subaerial or littoral, fluvial, glacial, or eolian, proceeds systematically through a series of stages; and while there is still more to be learned than is now known regarding the progress of mountain sculpture, enough is already safely understood to exclude the resort to erosion in general as a ready means of accounting for any desired result. It remains, however, to be seen whether not only the base but the face of the Basin ranges is consistent with the theory of block-faulting. The form of the valleys that are carved in the mountain face

will be first considered, and after this the form of the spurs between the valleys.

It follows from the scheme graphically represented in Figure I, that a very rapid and modern faulting of a very resistant rock mass in a very conservative climate would produce a mountain block having a notably smooth fault-face or escarpment along its front. On the other hand, the gradual and long-continued faulting of a weak rock mass in a destructive climate would produce a mountain block having well-developed ravines and canyons whose erosion had been accomplished during the progress of the faulting. The essential characteristic of such ravines would be a V-like cross-section even down to the ravine mouths; and as long as the uplifting of the mountain block actively continues, the streams that are dissecting it cannot widen their valley floors. Indeed, many of the smaller streams might be unable under such conditions to attain a graded slope even in weak rocks, and their channels would be marked by rapids near the base line of the mountain, where the V-ravine would suddenly open upon an alluvial fan, sloping gently forward to the waste-covered piedmont plain. It is only after faulting has ceased that the streams can advance in an interrupted progress toward mature development and widen their valley floors toward the mountain front; and only after faulting has long ceased can the valley floors be so far developed as to leave nothing but residual skeletons of the original mountain block between them. Variations in rate of faulting and in resistance of rock masses would produce many corresponding variations in ravine forms, many of which may be easily deduced, but none of which demand immediate consideration.

The points that need special emphasis in this connection are that the characteristic form of ravines and canyons, carved in a faulted mountain block during the progress of a long-continued and still active faulting, can be reasonably determined by deduction; that these forms are well specialized; and that their most notable peculiarity is the persistence of a V-section down to the mountain base, where the steep-walled ravine or canyon suddenly opens upon a gravel fan that slopes forward to the wide piedmont plain. For example, the canyon of Plate 5, B, opens on the face of Plate 6, B. It goes without saying that this peculiarity of canyon form is impossible in a residual mountain, carved by the extensive erosion of a once much larger mass, unless the most special conditions conspire to produce it. Such conspiracy is found, as has been said, in the stratified Appalachians, where the belts of resistant sandstone, interstratified with much weaker shales and limestones, now stand

in relief as residual mountains in which the streams and rivers have cut sharp V-section ravines and notches. The resistance of the sandstones, on which the survival of the sharply limited mountain ridge depends, is, therefore, also the cause of the narrowness of the ravines and notches cut in it by the streams; and it may be added that the sharpness of these forms is in part due to the relatively recent uplift that the middle Appalachian belt has suffered.

All the higher Basin ranges that I saw in the summer of 1902 are characterized by sharp-cut V-section ravines and canyons, narrow-floored and steep-walled down to their very mouths; typical examples are shown in Plate 5, from the Pueblo range, described below. All these canyoned ranges are so unlike in structure to the ridges of the stratified Appalachians that it is utterly out of the question to explain the former by the theory that is appropriate for the latter.

Rock canyon in the Wahsatch near Provo, Plate 4, A, has a narrow gravel plain near its mouth, probably the result of delta building in front of the mountain base during the presence of Lake Bonneville; but after going up the canyon a few hundred feet, its stream is found cascading on the more resistant strata, whose rising outcrops form prominent ribs on the steep canyon wall. The same features are observable in Slate canyon, Plate 4, B, three miles further south, except that the stream here being smaller, its descent is steeper, and it has accumulated hardly any gravels up stream from its Bonneville delta on the mountain front. The beds of both these streams have a rapid descent, and are not cut down as low at the canyon mouth as might be expected in view of the much lower level of the broad piedmont plain a little way forward from the mountain base. Some detention of their down-cutting must be ascribed to the temporary rises of the local baselevel during Bonneville time, and to the work of removing high-level delta gravels in post-Bonneville time; but this cause of detention does not seem nearly sufficient to account for the height of the stream beds over the plain. Hence not only the steepness of the canyon walls, the narrowness of their floors, and the rapid descent of their stream, but also the relatively high level of their mouths suggest recent uplift of the mountain block.

The general form of these two steep-walled canyons suggests not only that the up-faulting of the mountain block has been continued into relatively recent time, but that the uplift of the block by an amount equal to the height of the summits over the base (in the Provo Wahsatch) has been accomplished since the latter part of Tertiary time. The canyons have a much younger expression than that of the narrow valleys in the up-

lands of southeastern Pennsylvania, for there the streams have formed narrow flood plains and the valley sides are for the most part smoothly graded even in crystalline rocks; yet the elevation of these uplands is not of remote date. If it is thought unsafe to make a comparison between canyons in the arid interior basin of Utah and young valleys in our better-watered Atlantic slope, the Wahsatch canyons with their perennial streams may be compared with the dry side canyons of the Colorado canyon in Arizona. The expression of the two is much the same, allowance being made for the unlike attitude of the rocks. The chief difference between these two groups of canyons is this: those of the Arizona plateaus were cut down in a rising plateau mass by intermittent wet-weather streams working with respect to the sinking local baselevel, the intrenching Colorado; those of the Wahsatch were cut down in a rising mountain mass by more persistent streams working with respect to a relatively fixed local baselevel. The erosion of the Arizona canyons, trunk and branch, cannot have been begun earlier than the latter part of Tertiary time; the erosion of the Wahsatch canyons may well have had an even later beginning. The date assigned to the Wahsatch fault by King, on incomplete geological evidence, is the close of the Eocene; but this seems inadmissibly early in view of the sharpness of the Wahsatch peaks and spurs and of the enormous amount of erosion accomplished in the plateau province in post-Eocene time.

It should be noted, however, that certain through-going streams in the Provo district have valleys that are more maturely opened than the canyons just considered. The so-called canyons of Provo river, Hobble creek, and Spanish fork are all relatively open, with moderately steep, frequently graded side, slopes. This seemed to me in part due to the occurrence of weaker rocks where the through-going streams have cut down their valleys, but I am not sure that this explanation applies in all cases. It may be that in some examples the more open valleys are connected with differences in the date, amount, and rate of faulting. Some of the through-going valleys are nevertheless of true canyon-like form: such is Weber canyon, which is followed from the east by the Union Pacific railroad into the Great Basin at Ogden; and also Ogden canyon, a few miles further north, if the maps may be trusted.

The part of the Wahsatch range next north of Spanish fork canyon, here called the Spanish Wahsatch, Plate 1, A, is beautifully carved with sharp ravines which preserve their narrow floor and steep walls directly to the mountain base. Two of these ravines were visited. The beds of their wet-weather streams pitch forward at an angle of from 22° to 34°,

steepening near their mouth; the slope of the side walls is 30°. All the ravines open close to the level of the Bonneville beach, instead of being cut down nearer to the level of the piedmont plain; as in the Provo Wahsatch, this peculiar relation should be here also at least in part ascribed to the recent up-faulting of the mountain block.

The Wahsatch range has many other canyons and ravines of similar form, so far as observation from the plain in front of the mountains can determine, and so far as description by local observers testifies.

The southwestern slope of the Santa Rosa range north of Cane spring deserves further statement. I had time to examine its general features from a spur next south of Cane spring, whence the mountain front was seen somewhat to the right of the view shown in Plate 2, B. The strike of various ledges outcropping on the bare mountain flanks was in general northeastward; that is, about at right angles to the trend of this part of the mountain base. The dip of the ledges was steep southeast, or nearly vertical. Rock structure was, however, very faintly exhibited as a rule; the mountain mass is for the most part worn to the stage of smoothly graded summits and spurs, whose graceful forms were beautifully brought out in late afternoon light. The spurs terminate in strong slopes, sometimes maintaining convex longitudinal profiles almost to their base. The valleys and ravines are steep-walled and narrow-floored to their very mouths. The mountain base is of long and gentle curvature, here convex to the southwest. Faint scarps in the washed gravels close to the mountain base were seen at several points, and were noted as indicating modern faulting. The gravel wash extends far forward on an even slope, thus suggesting a vigorous discharge of waste from the mountain valleys. For several miles east of Cane spring, the strong wash from the mountains on the north meets a much weaker wash from a series of low spurs on the south; these spurs descend gently, some reaching further forward than others, and all blending by gradual concave slopes with the inclined gravel plain before them. So distinct a contrast between the forms of the mountains on the north and those of the spurs on the south must have a meaning. No meaning seems so probable as that which associates the mountain with strong block faulting and active carving, both continued into recent time, and the spurs with a long period of undisturbed erosion.

As a characteristic of this arid and thinly settled region, note may be made of the fruit ranch of a Basque at the mouth of one of the valleys in the Santa Rosa mountains. The small stream from the valleys supplies water enough to irrigate an orchard of a thousand apple-trees and

some alfalfa fields: the alfalfa serves for local needs; the fruit is sold to neighboring ranches and villages. Another valley supplies water for some alfalfa fields belonging to the ranch at Cane spring. This spring itself seems to rise where the long wash slope from the mountains on the north comes against the rock that descends from the spurs on the south. Every drop of water available in the growing season is used. Storage reservoirs in the mountains would increase the summer supply, but such reservoirs would be so soon filled with waste — should they indeed escape destruction by a cloud-burst torrent — that the cost of their construction would, it is to be feared, never be repaid.

The Mountain Face. — The study of mountain morphology is so little advanced that one encounters difficulty both as to method and terms in

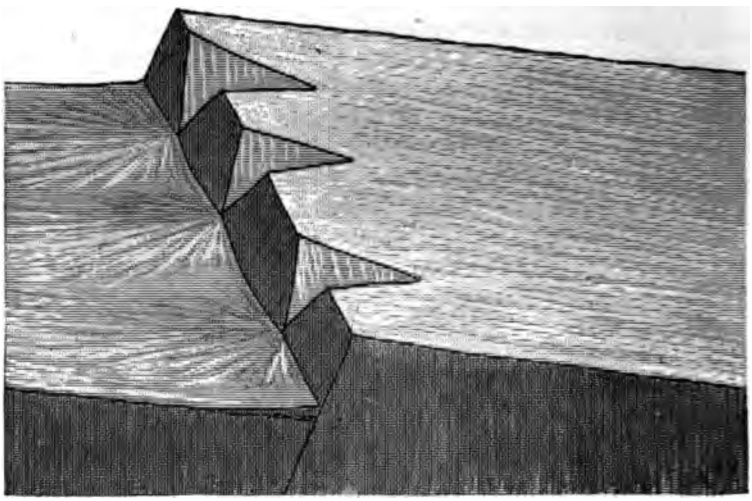

FIGURE 6.

Diagram showing notches in the front of a young tilted block; some of the front edge of the block still remains.

attempting to present a definite account of mountain forms. It is evident, however, that the face of a range, carved on the fault scarp of its tilted or lifted block, should present certain features characteristic of such an origin, and that these features should be deduced as carefully as any others in the mental construction of the type example, so that their occurrence or absence in actual ranges may be determined. In no other way can it be ascertained whether the face of the range as well as its

base and its canyons testify in favor of block faulting. The next following paragraphs therefore attempt to discover the forms that should characterize the ideal case of a faulted block of homogeneous structure whose faulting has progressed at a slow and relatively uniform rate, so that the sides of the ravines that are eroded in it shall be weathered back to

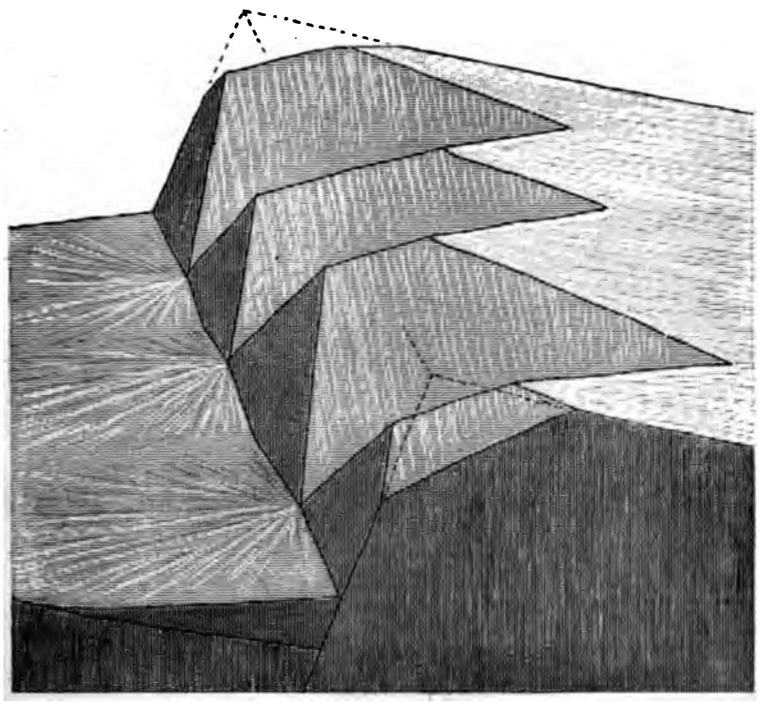

FIGURE 7.

Diagram showing notches in the front of a young tilted block, more uplifted than in Fig. 6; nothing of the front edge now remains.

graded slopes about as fast as the fault block is raised. Three significant stages of faulting and erosion may be considered. In an early stage, Figure 6, the low fault scarp is notched by ravines whose location and length are determined by the site of prefaulting inequalities in the upper surface of the block. Adjacent ravines have not yet widened sufficiently to consume the edge at the top of the block between them. In a later stage, Figure 7, the block is raised higher, the ravines are worn deeper and further back, some of them being larger than others. Noth-

ing of the upper front edge of the block now remains, for the flaring walls of the ravines now meet in a sharp ridge crest that rises backward from the vertex of a triangular facet on the block front, toward the top of the block. In the third stage, Figure 8, the block is raised

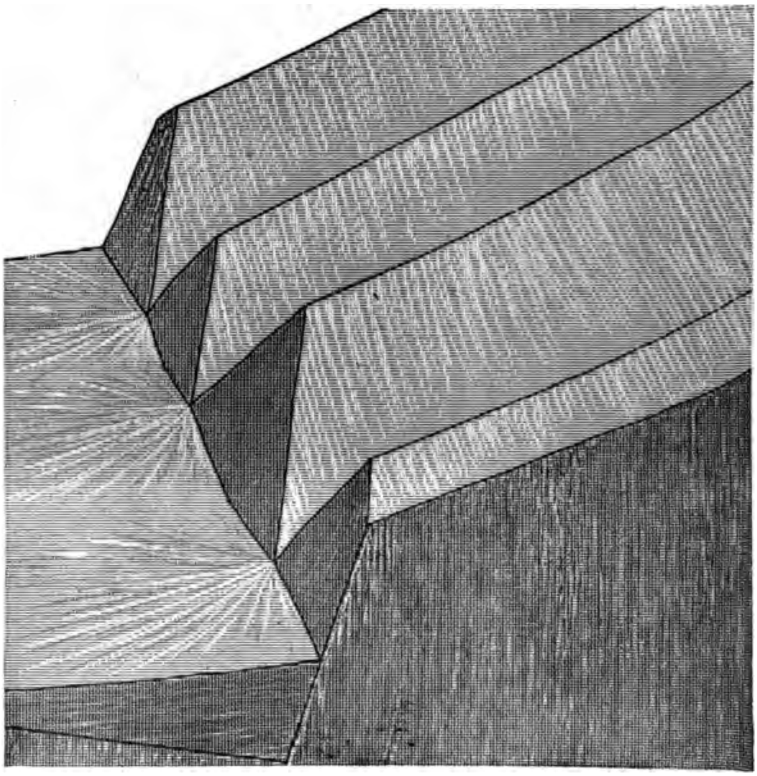

FIGURE 8.

Diagrams showing spurs and deep ravines in the front of a tilted block, uplifted so high that nothing of the upper surface is here seen.

still higher, and the ravines have become still longer and deeper; at this stage the mountain crest might become serrate, and its back slope would be well dissected. The long sharp-crested ridges between the larger front ravines are still terminated by triangular facets, very systematic in form and position, with their bases aligned along the mountain front. The spur sides and the facets themselves will have

suffered some carving, as is shown in Figure 9, where some of the terminal facets are enlarged. The moderate dissection of the large facet by small ravines results in the development of several little basal facets along the fault line, where they form the truncating terminals of several

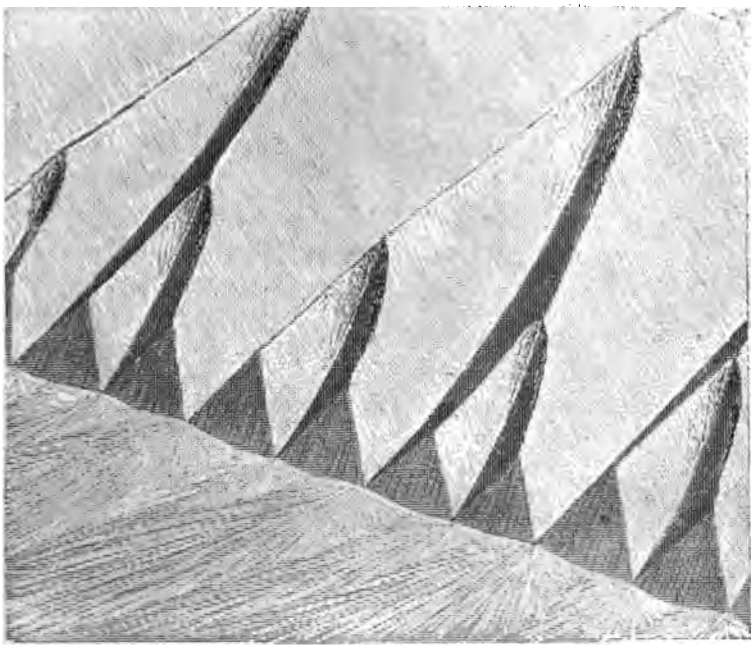

FIGURE 9.

Diagram of dissected terminal faces of main spurs, showing small basal facets between short ravines; drawn on a larger scale than Figs. 6–8.

little spurs. These basal facets are of importance in this stage of dissection, for they have suffered the least change of any part of the mountain front.

We are thus led to conclude that the features of special significance as the necessary result of long-continued faulting, persistent into the recent period, are: first, the sharp-cut, narrow-floored valleys which have already been considered; and secondly, the large and small terminal facets of the spurs, whose bases show a notable alignment all along the mountain front.

If faulting be supposed to cease after the stage of Figure 8 is reached,

the valleys will widen without much deepening at their mouths, the spurs will be narrowed, and the truncating terminal facets will in time be so far consumed that the spurs will become pointed, as in Figure 10. The further erosion progresses into maturity, the farther will the points

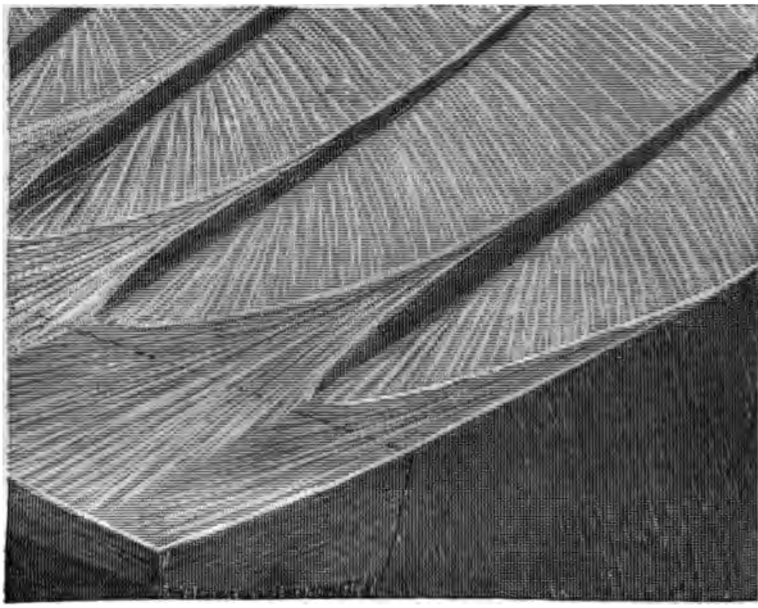

FIGURE 10.

Diagram of tapering spurs between open valleys in a late mature stage of a tilted block; same scale as Figs. 6–8.

of the wasting spurs withdraw from the fault line, and the more perfect will be the relation of structure and form; but as old age is reached this relation is more and more suppressed. It is evident that late maturity or early old age will introduce the system of interlocking valleys and spurs already described as characteristic of subdued residual mountains.

Spurs and Terminal Facets of the Wahsatch Range. — The Spanish Wahsatch, opposite the villages of Springville and Mapleton, presents a group of forms that resembles to a singular degree those represented in Figures 8 and 9. The mountain base has already been referred to as shown in Plate 1, B, an examination of which will now discover the profiles of a series of basal spur-facets, sloping at an angle of 38° or 40°, and possessing remarkably systematic forms which correspond closely to

those deduced for the ideal type in its maturely dissected stage. A front view of the facetted spurs is given in Plate 1, A. The ridge or crest line of the spurs slopes at angles that do not vary greatly from 25°. Figure 11, enlarged from photograph and sketch, presents a more detailed view of this part of the Wahsatch, in which the sharp-crested ridges, with their peculiarly systematic terminal gullies and facets, rise between the sharp-cut ravines of the mountain front. The difference between these beautifully sculptured forms and the more rigid diagrammatic features of Figures 6 to 10, is not a difference of kind, for every element in the ideal view is matchable with a corresponding element in the actual view; it is rather a difference due to the occurrence in nature of innumerable

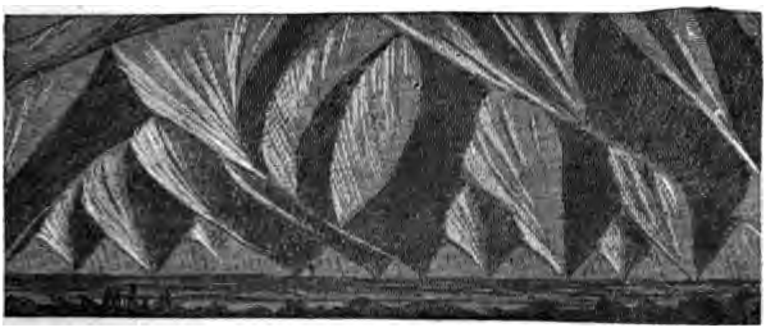

FIGURE 11.

View of the ravines, spurs, and terminal facets of the Spanish Wahsatch, looking east; drawn from sketch and photograph.

little irregularities, the result of slight variations of rock mass and of sculpturing process, whereby actual mountains depart in so pleasing and graceful a manner from the hard and conventional lines of diagrams. In spite of these differences, the notable characteristic of this part of the Wahsatch front is its model-like form, every element of which is so systematically arranged that it can be understood: and thereon depends much of its attractiveness. The expression of its features is open and frank, without that complication of unresolvable elements which makes the meaning of larger mountain forms so difficult of full understanding. One reason for the simplicity of form here exhibited is the simplicity of rock-structure in the mountain block. The strata of which it is built lie nearly horizontal in the district that we examined, and none of them are sufficiently unlike their neighbors in strength or weakness to determine the occurrence of strong cliffs or benches. There

are indeed several delicately embossed contouring lines on the spur slopes by which the structure of the mass is indicated in the distant view; and on climbing the slopes there are abundant small outcrops by which the inference from the distant view is confirmed; but as a whole the slopes are graded and cloaked with a thin cover of creeping waste, so that the observer's attention is not too soon diverted from the study of mountain sculpture by an emphatic exhibition of mountain structure.

I first saw the spurs, facets, and ravines of this mountain front from the passing excursion train of the International Geological Congress in 1891 ; but they were then only regarded as "peculiar." They were seen a second time on returning from a Colorado canyon excursion in 1900, and on that occasion, although they were then again observed only from passing trains northward on one road in the morning, and southward on another in the afternoon, the possibility and necessity of explaining them as a result of erosion on a faulted block was recognized. During the summer of 1902 my party made a special visit to these significant spurs, walked along their base for a short distance, ascended the slope of one of the facets, and came down again by the ravine alongside of it. There seemed to be no escape from the conclusion that extensive and recent faulting of the mountain block is here indicated, not only by the complete absence of the mountain rocks west of the almost rectilinear base line, as already set forth, but also by the detail of form on the mountain face, and particularly by the well-defined facets in which the spurs terminate.

The late afternoon view of the Wahsatch range from the shore of Utah lake brings the mountain forms clearly forth. The eye, after wandering along other less intelligible parts of the range, turns repeatedly to the block north of Spanish fork canyon with enjoyment of the fuller meaning found there. Elsewhere one's curiosity is excited; there it is satisfied. After the sharply defined terminal facets of the mountain spurs are found to be systematic elements of form in the Spanish Wahsatch, they may be recognized in many other parts of the range, but nowhere, so far as I have seen, with the model-like distinctness of development that is exhibited in the example just described.

When the Wahsatch near Provo is seen from a point not too near its base, several spur-facets may be distinguished between the canyons and ravines by which the mountain front is scored; but the edges of the facets are dull, like the edges of a crystal of apatite. In the Spanish block, the sharp-edged facets tempt one to sketch in outline: in the

Provo block, it is by no means so easy to do justice to the mountain form in an unshaded drawing. One reason for this is that the ravines here are not very deeply carved — except the larger ones, called canyons, whose streams head in subsequent valleys back of the frontal ridge — and hence the spurs do not stand forth between the ravines in strong relief. Moreover, accompanying and perhaps causing this loss of definition in the spurs and facets, there is an increased variety of texture in the rock mass, whereby certain resistant strata stand forth bare and prominent between weaker neighbors; the attention is thus involuntary somewhat distracted from sculpture and turned toward structure. The facets are nevertheless undeniably present, and in essentially the same relation to spur and base line as is shown in the type diagram, Figure 8. The southern end of the Provo block possesses the most distinct examples, some of which will be described in the following section.

The Wahsatch spurs that descend near Little Cottonwood canyon, between Provo and Salt Lake, are systematically terminated by clearly recognizable facets.

The Ogden Wahsatch also offers illustrations of the systematic facetting of its spurs, those adjoining Weber canyon being the most distinct. Further north, back of the city of Ogden, the facets are round-edged, yet distinctly recognizable as systematic elements of form, like those of the Provo Wahsatch.

The spurs of several other ranges, seen from train and stage in Utah and Nevada, were terminated by facets of more or less distinct form. The spurs of the Santa Rosa range were more rounded than many of the others, and the terminal facets were indistinct. The eastern face of Pine Forest mountains in northern Nevada is notably steep and scarp-like, descending to a relatively rectilinear base. The scarp is sharply cut by narrow valleys which remain narrow to their very mouths. Some of the spurs end in rounded facets. Signs of recent faults in the gravels at the mountain base were noted, but at too great a distance to feel certain of their meaning. The height of the range gradually decreases to its trailing southern end. In this range more clearly than elsewhere the narrow valleys seemed to be cut beneath a rolling upland of earlier origin.

The Spur-Facets are not Wave-Cut. — The terminal facets of the Wahsatch front rise over the Bonneville beaches in such a way as to suggest a possible origin as wave-cut cliffs. It is not to be doubted that waves could, if time be allowed, cut off the points of spurs so as to truncate them in triangular facets, but in that case the facets should be associated with certain other features which are significantly absent from the Wah-

satch range. This may, as usual, be best demonstrated by consideration of the progress of wave work in an ideal case.

If the surface of a sea or lake should rise on a ravined mountain front, so as to gain an irregular shore line, ABCD, Figure 12, the promontories might in time be cut back to the straight shore line DFH, over which the spurs would then terminate in triangular cliff-facets, DKF, FLH. But in such a case, the valleys should not remain narrow-mouthed during the progress of the wave work, but should widen somewhat and allow the streams to develop flood plains on which they could wander a little; and after the lake waters had disappeared, the facets should look out

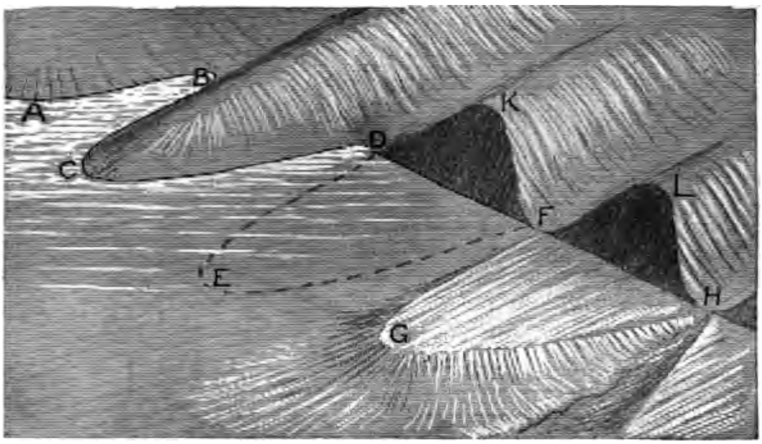

FIGURE 12.

Diagram of spurs cut by waves: ABCD, initial shore-line at time of submergence; DKF, cliff facet cut back in spur DEF; FGH, spur platform fronting its cliff facet FLH, after withdrawal of lake waters.

upon triangular rock platforms, FGH, systematically related in form and area to the facets. As a matter of fact the triangular rock-platforms and the widened valley mouths are wanting in every case that came under my notice. It cannot be supposed that the mountain front was cut back by waves at so low a level that the wave-cut platform is now concealed by mountain waste; for in that case the narrow ravines should also have been cut down to the same low level, instead of opening, as they so often do, rock-floored on the mountain flank, and allowing the streams to continue their descent on gravel fans that rise at the apex distinctly above the intermont plain. One of the best localities for the illustration of

these features is at the southern end of the Provo Wahsatch, northeast of Springville, Plate 3, B, where the base line curves from south to southeast. Several ravines furrow the mountain face, dividing it into a number of subparallel spurs, all of which are cut off by rather well defined triangular facets. If these facets are explained as shore-line cliffs, rock platforms should stretch from a quarter to a half mile forward from the cliff base into the plain: but no such platforms are to be seen. If any rock platform exists, it must be supposed that it was cut at a much lower level than that of the Bonneville shore line, and that it is buried under the sands and clays that cover the low ground: but the existence of a wave-cut platform at such a depth is inconsistent with the opening of the ravines in the mountain flank several hundred feet above the plain; the ravines would necessarily have been deepened by their streams as the cliffs and platforms were cut back by the waves; hence the supposition of a wave-cut origin for the facets cannot be favorably entertained: an origin by faulting is much more reasonable. It is noticeable that the stream lines in this part of the Wahsatch pitch with increasing steepness in the narrow gorge-like mouths of the ravines, thus hurrying between a gentler but still steep descent down the ravines in the mountain flank above, and a gentler descent through the Bonneville gravels on the way to the plain below. Indeed, the gorge-like mouths of the ravines seem to be incised somewhat below the base of a series of simply triangular facets, so as to give the spur sections the beginning of a house-end pattern, as if the faulting of the mountain block had been locally accelerated not loug ago. The features of this interesting locality would well repay a detailed study.

True wave-cut cliffs and their correlated rock-platforms may, as is well known, be seen at various points on the Bonneville shore line, but the cliffs are usually of much less height than that of the spur-facets in the Wahsatch front; and in no case had the rock-platforms that I saw nearly so great a breadth as would be demanded by the forward prolongation of the facetted Wahsatch spurs so that the slope of the spur crest-line should descend to the platform level. The facets of the Spanish Wahsatch front the basin of Utah lake, not over twenty-five miles broad from east to west: the Bonneville waters here must have been much less powerful than in their more open areas further north; yet these facets are much larger than the true wave-cut cliffs that are seen on more exposed parts of the old shore line. The best facets of the Ogden Wahsatch, above-mentioned as lying close to by Weber canyon, cannot have been much affected by the Bonneville waves, for during much of Bonne-

ville time this part of the mountain base was well protected by the growing delta of Weber river.

The Erosion of the Spur-Facets. — It is evident from what has been said in the section on the mountain face that the retreat of a mountain front from its initial fault scarp will be greater on the stream lines than on the interstream surfaces, and again greater at the apex of a facet than at its base. The concentration of drainage — even if it be only wet-weather drainage — along the stream line of the ravines, and the increase in the volume of the streams from head to mouth has given them strength enough to remove the waste that weathers and creeps down from the ravine walls. There is, however, at present no such concentration of removing agencies along the foot of the mountains; and as the duration of the Bonneville waters at their various levels has been but a small fraction of the whole life of the mountains, it may be said that there has prevailingly been no active agent available for the removal of waste from the mountain base between the mouths of the streams.

If the fault plane were vertical, a large amount of rock waste would have fallen from it, and in the absence of any effective removing agency along the mountain base, some of the waste should accumulate there as a talus, Figure 13, whose foot should advance in front of the fault line. The conspicuous absence of such talus makes it probable that the fault plane was by no means vertical, and suggests that the slope of the spur facets may not be greatly unlike the slope of the faults. In the Spanish Wahsatch, the small facets slope at an angle of 38° or 40°; in the Provo Wahsatch, the slope is from 32° to 38°. Certain ranges in northern Nevada had similarly steep basal slopes.

Other Parts of Block Mountains. — In the early stages of faulting, the back slope of a tilted mountain block should exhibit its prefaulting form little changed, except that all the slopes and streams which had been steepened by the tilting would show signs of more active erosion than the other parts. The lower part of the back slope would be buried under accumulating waste.

In a later stage of faulting, it might be impossible to recognize any survivors of the prefaulting forms, unless near the back base where the small depth to which erosion could penetrate would delay change. The back base line would expectably be much more sinuous than the front base line, for at the back of the range the gravels and sands of the intermont depression would mount obliquely upon a surface in which the inequalities of prefaulting time had been somewhat exaggerated by the revived erosion of the early stages of tilting.

In the early and later stages of faulting, both faces of a lifted mountain block would present features similar to those already described as occurring on the faulted face of a tilted block, while the upper surface of the lifted block would exhibit features dependent on revived erosion, such as are commonly found in uplifted regions. In young blocks of this kind, the intensity of revived erosion would rapidly increase toward the block border; in this respect the upland of a young block would present features very similar to those found in the Arizona plateaus that border on the Colorado canyon, or in the plateaus of western Germany which border either on the Rhine gorge below Bingen or the Rhine

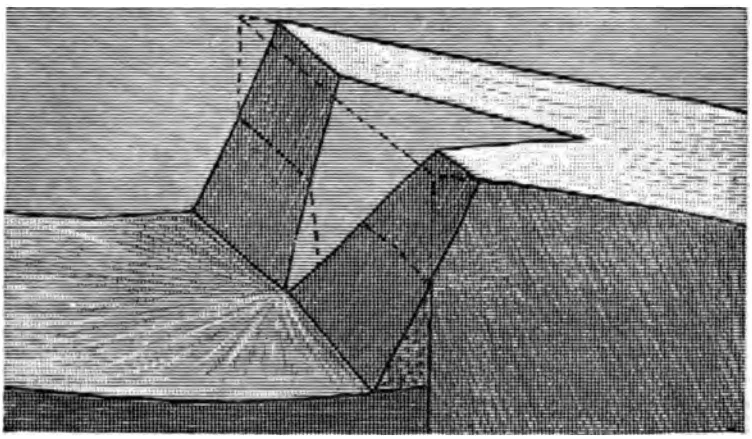

FIGURE 13.

Diagram of talus at the base of a vertical block front.

graben above Bingen; for so far as the dissection of an upland is concerned, it matters little whether its streams descend by a fault scarp to a lowland or by a canyon wall to a river.

In older uplifted blocks of longer continued faulting, the contrast of scarp and upland would be weakened; and after the faulting was far advanced, the contrast would disappear entirely. The battered retreat of both scarps, gnawed by retrogressive ravines, would result in transforming the upland into a more or less serrated ridge.

Many special conditions might be imposed upon these general deductions by assuming particular features of prefaulting relief and drainage. These conditions need not be entered upon here, because my observations did not go far enough to provide a large variety of facts with which

deductions of specialized types could be confronted. It may be noted, however, that the deduced features of the back slope of a tilted block are not so much unlike the forms of residual mountains as are those of the front of such a block. It is, therefore, not to be expected that tilted-block ranges can be recognized so well when their back is seen as when one looks at their expressive face. But when the features characteristic of the back slope of a tilted block occur on one side of a range while those appropriate to the faulted face occur on the other side, it is reasonable to look upon such a range as the result of block faulting.

The eastern side of the Santa Rosa mountains north of Winnemucca, Nevada, for example, does not imitate the well-defined base line of the western side, so far as I saw this range. The eastern valleys are open and well graded between spaced spurs. The same is true of the eastern base of Jackson range, whose western base has already been mentioned as suggestive of faulting. Moreover, in profile this range resembles a tilted block when seen from the north in such a way that its ravines are hidden behind its spurs. The crest line is near the western side where the slopes are precipitous, while the eastern slopes are much more gradual.

If any ranges have been carved from uplifted blocks, bounded by faults on both sides, they have — so far as the examples that I saw are concerned — reached the advanced stage of dissection in which the initial upland is carved into a serrate ridge. My line of travel seldom made it possible to see both sides of a single range, and hence my notes leave it uncertain in most cases whether a range with a well-defined base line on one side is similarly formed or not on the other side.

Modern Faulting. — It is certainly very significant that indisputable evidence of modern displacement should be found close along certain mountain base lines where abundant evidence of long-continued earlier faulting is provided by the mountain form. This has been so clearly pointed out by Gilbert and Russell that little space need be given to it here. Suffice it to say that repeated instances of scarps in gravel deltas and fans were noted last summer along the Wahsatch base, as well as along the border of certain other ranges to be described below. A distinct scarp in the gravels of the Bonneville beach is traceable all along the front of the Spanish Wahsatch, a little forward from the base of the facets, — Plate 1, A. The breaks in the delta of Rock canyon creek and in various other gravel deposits near Provo were easily recognized.

It is sometimes suggested that the displacements in the Bonneville gravels are more of the nature of superficial landslides than of deep-

seated faults. Taken alone they might perhaps be so considered; but taken in connection with all the associated features they cannot be regarded as independent of displacement in the underlying rock mass.

There is, however, one aspect of the modern faulting that deserves consideration. In all cases that I have seen, the modern movements are so placed that they must be taken as the continuation of long-maintained displacements whose total measure must, as a rule, amount to many hundreds or some thousands of feet. No other explanation has been found for the presence of such mountain masses as have been described above, standing in strong relief on one side of the fault line, while there are only gravels and sands to be seen on the other side. It is, of course, conceivable that modern faulting may have been here and there begun on new lines, essentially independent of the older fault lines, but such cases must be rare; for it is to be expected that, if a modern fault occurs on a new line, it should run across country indifferent to pre-existent structures. Such a fault might run obliquely across an intermont plain, then traverse a mountain range, and continue into another plain beyond the range, the whole length of the fault being marked by a scarp of more or less distinct form. The Great Basin has not yet been carefully enough explored to prove that no such faults occur; but the region is well enough known to warrant the provisional statement that new faults of a date as recent as the scarps of the Bonneville deposits are rare, except in connection with old faults.

On the other hand, there seem to be many ancient faults in the Basin ranges on which movement ceased long ago. This is shown by the obliteration through erosion of relief due to faulting; or sometimes by so great an excess of erosion in the uplifted block over that in the thrown block, that the thrown block now stands above the lifted block, the fault scarp being thus topographically reversed by erosion. Many examples of these kinds are given by Spurr. It does not, however, seem admissible to argue from the absence of modern movement on these faults, or from the apparent absence of modern faults within the ranges, that no long-maintained faulting can have taken place along the range borders. That must be determined by evidence furnished by the borders of the ranges themselves.

The Measure and Distribution of Faulting. — It may be noted that only an incomplete measure of the total movement in block faulting is determined by the difference of altitude between the mountain base and the reconstructed crest in a lifted or tilted block: for in addition to this measure, there must be a certain supplement by which the inequalities of

the prefaulting surface have been depressed out of sight in the thrown block. Advanced old age in the prefaulting cycle, and youth or early maturity in the present cycle, are the conditions demanding the least measure of block faulting; for the small relief of advanced old age in the preceding cycle would be consistent with the easy burial of all rock surfaces near the fault line in the thrown block; and youth or early maturity in the present cycle would call for the least addition to the existing height in reconstructing the crest of the mountain block near the fault line.

It is worth while to call attention at this point to a corollary that follows from the provisional conclusion above stated regarding the prevailing absence of modern faults except along the base lines of certain ranges where independent lines of evidence lead to the belief that the modern movements are but the latest displacements on faults of much greater age. The corollary is this: the total displacement on these long-lived faults must be usually greater than the ordinary measure of prefaulting relief in the Great Basin region. For the fault lines must have originally run indifferently to the structure of the region, and therefore indifferently also to whatever relief the region had assumed when the faulting began; and yet the thrown block is now as a rule completely covered with gravels and sands washed from the heaved block. Exceptions to this rule are found at certain points, but they are rare. If further exploration confirm the provisional conclusion above referred to, this corollary may have some value.

In this connection it may be noted that the great measure of displacement inferred by King for the Wahsatch fault (b, 745) seems unnecessary. If the folded strata of the range had been reduced to moderate relief by prefaulting erosion — and this seems not improbable if one may judge by the enormous volume of the Eocene (Vermilion creek) Tertiary to the east (King, b, 745) — the measure of the fault need not be more than enough to raise the crest of the range above the rock floor that is buried under the sediments of the Salt Lake basin; that is, from 6,000 to 10,000 feet instead of 40,000.

It was suggested by Van Hise in the discussion of this subject at the recent Washington meeting of the Geological Society of America that the displacement in faults of large throw, such as those by which the Basin ranges have been formed, are believed to be, is usually distributed on grouped fractures instead of taking place on a single plane of displacement. All the ranges that came under my observation last summer are non-committal on this point, except in so far as the absence of dis-

coverable fractures in the front part of the mountains requires that any additional fractures besides the one which determines the mountain base should be forward from it, and concealed under the gravels of the piedmont plain. Certainly if there are distributed faults in the Spanish Wahsatch block, the displacements on the minor faults within the block must have ceased long enough ago to have been obliterated, so far as surface form is concerned, in the smoothly graded slopes of the spurs; while the movement on the main fault along the front margin of the block has continued to so modern a date as still to have distinct control over the form of the terminal facets.

An article of interest in this connection has lately been published by Mr. D. W. Johnson on block mountains in New Mexico, from which it appears that Sandia mountain, near Albuquerque, is a large block with its chief displacement along the strong escarpment that it presents to the west, but with many smaller displacements within its mass, thus confirming the suggestion of distributive faulting as made by Van Hise. The dynamics of faulting are, however, not yet so well understood that it is safe to assert the occurrence of distributive faulting in all block mountains. Surely no one could have hesitated to believe that the Sandia block was faulted, even if minor faults had not been found on its back slope. In the plateau province of Utah and Arizona several of the greater faults are demonstrably on relatively simple fractures; for the strata of the adjoining blocks come close to the fault line without noticeable disturbance; there is room for fault breccias fifty or one hundred feet wide, but apart from that the faults seem to be for the most part simple and clean cut.

It is evident that the examples of Basin ranges here described are alone too few in number to support any safe conclusion as to the origin of the Basin ranges in general. The Wahsatch range forms the eastern border of the Great Basin province, and although it seems to be of fault-block origin, it cannot be taken as a typical example of one of the isolated ranges within the Great Basin. The chief profit that comes from the study of the Wahsatch range is the definition of certain criteria by which fault-bordered ranges may be determined elsewhere; and this profit will be increased when the back or eastern slope of the Wahsatch shall have been studied in the same relation. The other ranges above mentioned have, however, a certain value in that they were chance samples, not selected beforehand because they were believed to be faulted blocks, but observed as they happened to be passed while the observer was on his way to other points. They thus serve to indicate at least a probability that other ranges in the same region have a similar structure.

The Pueblo-Stein Mountains. — By taking a three-day dusty stage ride northward from Winnemucca, Nev., I was enabled to give a week to the study of the Pueblo and Stein mountains that cross the Nevada-Oregon boundary a little west of the north and south line marked by the post-offices of Denio and Andrews. The stage road carried me past the Santa Rosa, Jackson, and Pine Forest ranges, of which some mention has already been made. The route for part of the distance lay on the dead-level gray silt plain of the extinct Lake Lahontan, whose successive shore lines were traceable at various heights on the enclosing slopes. A long gravel spit, hooked to the east at various levels, stretched northward from the Jackson range to Mason's crossing of Quinn river.

The general result of this week's work gave me the impression that the Pueblo-Stein mountain range is more eroded than would be inferred from Russell's description of it (b, 439,444); but there can be no reasonable doubt that it represents a long fault block. The following pages contain a direct statement of the evidence to this conclusion, without analysis of the method by which the conclusion is reached. The analysis has been sufficiently stated in the preceding pages; its results may now be employed without restatement of the method of reaching them. This is the historical order in the development of methods of investigation, with the time element condensed. When a geologist nowadays describes vertical strata of conglomerate as of sedimentary origin, he does not again go over de Saussure's argument concerning the conglomerate of Valorsine; when a physiographer now asserts the occurrence of a subsequent valley on the evidence of stream course and rock structure, he need not repeat the argument by which subsequent valleys were first explained by Jukes in the basin of the Blackwater. These are settled questions and may therefore be treated by the short and direct method that steps at once from observation to conclusion. So may the question of block mountains be treated by the short method, provided the complete method has been tried and found valid.

The Pueblo mountains of Southern Oregon, Figure 14, overstep the state boundary at Denio and extend about ten miles southward into Nevada. They trend northward to a high dome 15 miles north of Denio, and then fall off in a broad westward re-entrant back of Doane's and Field's ranches. The high serrated range north of the re-entrant is the beginning of the Stein (or Steen) mountains. The Pueblo mountains consist of two ranges for most of their length. The eastern or front range, Figure 15, is made of ancient crystalline rocks, such as diabases and mica schists. The western or back range is made of bedded lavas,

basaltic so far as I saw them, whose westward dip of 15° or 20° is well expressed in a series of east-facing escarpments. Paired wet-weather subsequent streams drain the longitudinal depression between the two ranges, and their gathered waters escape eastward by deep-cut narrow-floored, steep-walled gorges through the front range to the broad plain known as Alvord valley. Russell marks a fault along the intermediate depression (b, 444, Pl. LXXXIV.); but the relation of the western lavas to the older rocks of the eastern range, as seen from the Stein mountains, Figure 16, from Doane's ranch near the north end of the range, and again in the depression between the ranges back of Deegan's, seemed to be best explained by normal superposition of the lavas on the crystal lines, followed by tilting and erosion without faulting. The depression between the front and back ranges is thus to be interpreted as a series of normal subsequent valleys, eroded along the weaker basal members of the lava beds by branches of streams that transect the eastern range and that are probably persistent from an earlier pre-faulting cycle of erosion.

The eastern base of the mountains is, however, unquestionably determined by a fault on which a total movement of several thousand feet has probably taken place, the latest displacements being of recent date, as Russell has shown. The base line of the range is of gentle curvature, indifferent to the structure of the mass. An excellent illustration of this is seen a mile or more south of Catlow's ranch, where a boldly outcropping rib of strong rock, standing oblique to the trend of the range, terminates evenly with the adjoining weaker rocks at the mountain base, and the face of the rib seems much sheared and broken. The ravines and gorges through which the range is drained are steep-walled and narrow to their mouths. The spurs between the ravines are abruptly cut off by the base line, and show no tendency whatever to trail forward into the plain.

Recent faulting along the mountain base is shown by several topographic features. At a number of points near the northern end of the range, between Catlow's and Doane's, open graded valley floors now stand a hundred feet or more above the mountain base, and are sharply trenched by the streams that formerly graded them. Uplifted and dissected fragments of broken fans are often seen one hundred feet or more above the mouth of a gorge, an excellent example of this kind being found back of Denio, while others occur near Catlow's. In general, the summits and higher slopes are of moderate declivity, frequently well covered with waste and exposing few ledges; while the walls of the cross-cut gorges

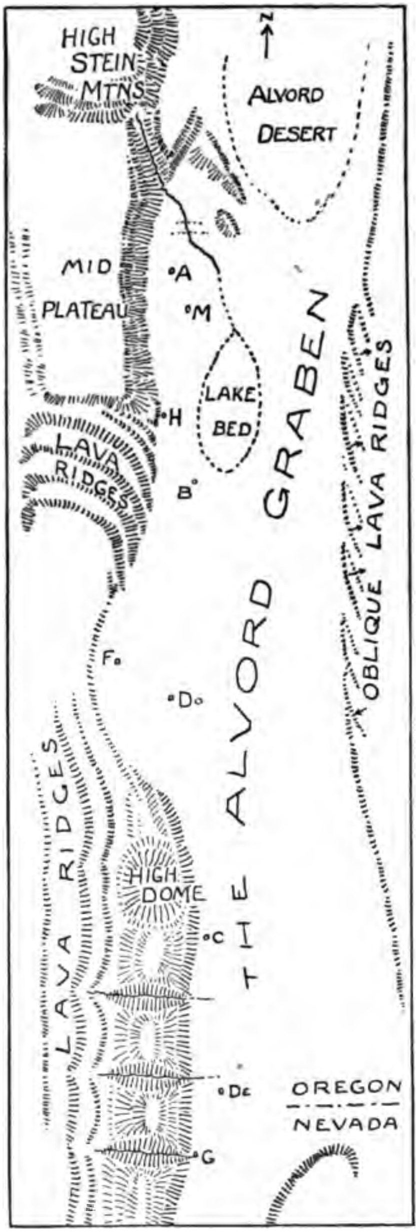

FIGURE 14.

Rough map of the Pueblo and Stein mountains. The side of the map is fifty or sixty miles, north and south. A, Andrews; B, Borax works; C, Catlow's ranch; De, Denio; Do, Doane's ranch; F, Field's ranch; G, Deegan's mine; H, Hollis's ranch; M, Miranda's ranch.

are steep, with abundant ledges, and in some cases the gorge walls steepen as they descend to the stream line. The slopes of the spur profiles commonly steepen toward the front base line; their general descent is at angles of from 10° to 25° ; but they often steepen downwards to 30° or 35°. The spur terminals are, however, well rounded, and but faintly recall the sharp-edged facets of the Spanish Wahsatch.

The southern part of the Pueblo range offered the best illustrations that I found of the trailing end of a faulted block, less dissected than the middle part and therefore probably representing a subrecent increase in the length of the block by a southward extension of its marginal fault. The front base of the range is here as elsewhere oblique to the structure; the crystalline rocks disappear first, and the lava monocline continues several miles further south

before dying out. The frontal escarpment of the monocline is very straight and but little dissected; the fans at its base are low, and a very gentle slope of alluvium leads from the base line to a dead level playa, half a mile to the east. The lava monocline is somewhat complicated by a transverse fault and a transverse monoclinal fold; but the frontal escarpment pays no attention to these disturbances.

The Stein mountains, Figure 14, continue the general line of the Pueblo mountains, although separated from them by the westward re-entrant already mentioned. The structure of this range is, however, unlike that of the other in consisting almost wholly of lavas for at least as far as some distance north of Andrews. The lavas resemble basalts and andesites, commonly porphyritic. The range may be conveniently described in three parts: the southern part is a warped monocline, dipping south and southwest, and obliquely cut off on the east by the north and south mountain base; the crest of this part of the range is serrated. The middle part is a plateau-like mass, with gentle western dip. The northern part is much higher than the rest; it was generally hidden in clouds or haze during my visit, and its structure was not determined.

I had an excellent view over most of the southern part of the range from the southeast corner of the middle plateau section, whence a great extent of country is disclosed. Alvord valley has every appearance of being a graben, limited by a fault on the east as well as the west; many low ranges trending to the south-southeast are obliquely cut off in a notably even line along the eastern valley margin. To the northeast, an escarpment bordering the valley is banked up with sands blown from the extensive playa of Alvord desert which occupies that part of the depression.

Not only is the Alvord depression seemingly a trough or graben, but the southern and middle parts of the Stein mountains are carved in what seems to be a lifted block, with a fault along the western as well as along the eastern border. The reason for this opinion cannot be presented as conclusive, for it is based only on what was seen from the point of view above named, yet there is little doubt in my own mind of its being correct. The southern and middle division of the range appeared to be evenly cut off along their western border, and this appearance was especially distinct for the southern division where the western border trends nearly square across a series of monoclinal ridges and valleys. The mountain block is ten or twelve miles wide, and is succeeded on the the west by a brown-gray plain, at 1,000 or 1,500 feet lower than the ridges, and 2,000 or 2,500 feet lower than the middle plateau division.

The monoclinal structure of the southern division has a strike in its western part to the west-northwest, with a southerly dip of 15° or 20°. Erosion has developed a number of well-defined ridges and valleys, and the generally accordant heights of the ridges as they rise gradually eastward suggests that the monoclinal mass had been much eroded previous to the uplift whereby the present dissection was initiated. As the ridges

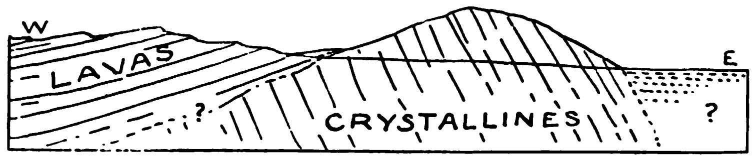

FIGURE 15.

Cross-section of the Pueblo mountains, looking north.

approach the crest of the range, which lies about three miles from its eastern base, the strike of the monocline turns to the southeast or south-southeast; the harder beds in the monoclinal ridges rise eastward to form the peaks, while the valleys of the monocline may be traced upward to the notches in the serrated mountain crest. On the eastern slope, the harder beds form benches that descend obliquely southward toward the eastern mountain base, where they are successively and evenly cut off.

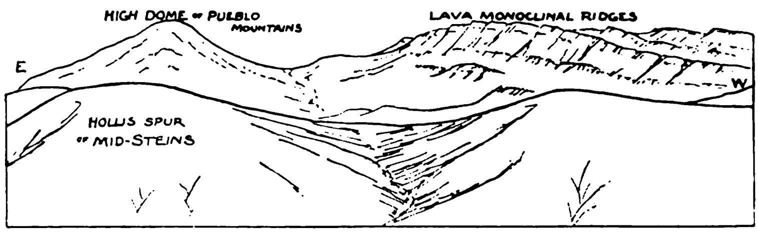

FIGURE 16.

View of the north end of the Pueblo mountains, looking south over the Hollis spur of the Mid-Stein mountains.

This form can be easily explained as a block of a baselevelled monoclinal mass, lifted and somewhat tilted to the west, and maturely eroded; but I find it difficult to explain it in any other way. A subrecent pause in the uplift of the block is indicated by the occurrence of well-defined graded basal slopes, independent of structure, now raised several hundred feet above the Alvord plain and dissected by numerous streams.

During this pause, the definition of the mountain base would have been much less distinct than it is to-day; indeed the base line would have been obliterated along a considerable fraction of the mountain front. Renewal of uplift has made the base line well defined to-day in the southern division of the range, but the streams on the aggraded floor of Alvord valley do not share in the revival by which the same streams on the mountain flanks have trenched the old graded slopes. A considerable period of time must have elapsed since the original uplift of the block began, for the crest of the range is now worn two or three miles back from the eastern base.

The middle division of the Stein mountains, Figure 17, is a monocline of so gentle a westward dip that it possesses a broadly rolling

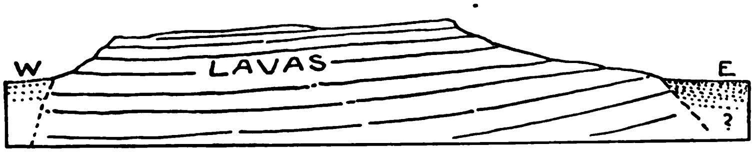

FIGURE 17.

Cross-section of Mid-Stein mountains, looking north.

upland surface, limited on the east by the strong escarpment which falls 2,500 or 3,000 feet to the Alvord trough, by a lower escarpment which overlooks the monoclinal ridges and valleys on the south, and by a strong escarpment again on the west. I believe all these escarpments have been worn back from fault lines, and there is some reason for thinking that the fault between the two divisions of the range, trending west-northwest, is older than the meridional faults on the east and west; but I will leave the discussion of this point to some one who can treat it in greater detail. As in the southern block, the crest line of the eastern block is now worn back two or three miles from base, indicating a long period since the block was first uplifted.

The face of the eastern escarpment presents many graded slopes between the ledges of more resistant lavas. The spurs between the obsequent ravines by which the escarpment is dissected usually descend with concave slopes toward the plain; but a short convex profile is often seen as the spur reaches the base line. The lower parts of many spurs exhibit well-defined graded slopes on the interstream surfaces, but the spurs are now rather sharply separated by the ravines, and thus indicate a prolonged pause followed by a subrecent uplift.

For the greater part of the range front, the fans that spread forward from the ravines are not faulted, but near the junction of the southern and middle blocks, subrecent and recent faulting is conspicuous. The most interesting locality is near Hollis's ranch, Figure 18. Here several strong bluffs rise rather boldly from the plain, forming terminal escarpments to spurs whose interstream surface, 600 or 800 feet over the mountain base, seems to have been well graded and reduced to small relief before it was cut by the streams that are now eroding sharp ravines in it; but the same streams run forward on aggraded gravel fans east of the mountain base line. The bluffs between the streams occasionally show outcropping ledges, but most of the bluff face is an even slope of slide-rock at an angle near 35°. Just north of Hollis's ranch, the bluff must be nearly 1,000 feet high, but it rapidly diminishes in strength north and south; and a mile and a half or two miles from the highest part of the bluff, the mountain base is of the usual gentle expression. The largest stream that cuts the bluff has a sharp-cut gorge next north of Hollis's ranch, whose irrigated fields lie on the fan that the stream has built. Very recent faulting is indicated by fragments of an older fan, now standing about 150 or 200 feet above the present fan on either side of the canyon mouth. Next north and south there are two "hanging valleys," 500 or 600 feet over the plain, the like of which was not noted elsewhere along the Stein mountain front.

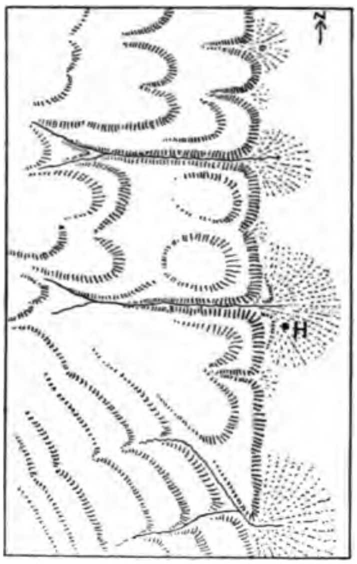

Figure 18.

Rough map around Hollis's ranch. The side of the map is five or six miles, north and south.

Some of these local features might be explained, independent of faulting, by the occurrence of a mass of unusually resistant rock at this part of the mountain base; but in that case it might be expected that a greater number of outcrops would be seen on the bluff faces and in the ravine walls. As far as the rock was examined, it seemed to be a porphyritic andesite, similar to other lavas of the mountain block.

Moreover, a mass of resistant rock could hardly be expected to be limited, except by a long block fault, so close to the line of the general mountain front; and it can hardly be a matter of chance that just where the general form of the mountain base suggests the most extensive subrecent faulting, there should occur the strongest recent fault as indicated by a broken gravel fan. Accepting then the conclusion that faulting is responsible for these basal bluffs, it may be noted that they are roughly in the stage of dissection indicated in Figure 6, except that all the edges are rounded off; but the initial upland of Figure 6 is here represented by the graded interstream surfaces that had been worn down to gentle slopes before the subrecent faulting began. There is some reason for associating this renewed uplift with the fault that has been above suggested to separate the southern and middle division of the range; but more detailed field work is necessary on this point.

The northern part of the middle Stein escarpment is breached by a large valley that comes southeast from the high Steins, and a small plateau-like block is thus cut off from the main mass as shown in Figure 14. Several low lava-bed monoclines, of gentle dip to the southwest, extend southeast from the detached block; they gradually dip underground near the southern end of the Alvord desert (playa) and their trend very strongly suggests a connection with the monoclinal ridges of similar strike on the eastern side of the Alvord trough. It is certainly reasonable to infer a fault with downthrow on the southeast between these low lava monoclines and the high detached block that overlooks them.

The Quaternary lake that Russell has described as occupying the Alvord trough left shore lines of moderate strength at various levels up to a few hundred feet over the present lake bed plain. The best examples noted are seen on the low lava monoclines, just mentioned, where faint benches are developed; in the embayment of the main depression that heads between the low monoclines and the main escarpment of the middle Stein plateau, where two cross-bay bars were built to a height of 10 or 20 feet, about a mile north of Andrews; beneath the strong bluffs just north of Hollis's ranch, where shore lines are associated with the chief fan delta of that district; and near the north end of the Pueblo range, between Doane's and Catlow's, where what seems to be a long spit was built out into the lake from the bend in the mountain front near the beginning of the re-entrant between the Pueblo and the Stein ranges.

To any one who wishes to give a month to the study of a well-defined

graben, bordered east and west by uplifted and well-dissected mountain blocks, Alvord valley may be highly commended.

The Shoshone Range. — On returning from Oregon, I passed by the northern end of the Shoshone range in north central Nevada in an east-bound afternoon express train on the Central Pacific railroad between Argenta and Shoshone. My notes, rather hurriedly written at the time, are as follows: "A very fine fault block, with manifest recent and subrecent faulting. Broken fans; light-colored basal slopes, ripped with gullies; uplifted grades, truncated spurs, revived streams in full-bodied spurs; spur tops dark gray, sides lighter; tops graded, sides ripped. Even fronted base, facing west and north; all excellent examples for study. At some points on west base, very short fans, as if plain had been depressed."

This specimen of a block mountain interested me greatly. It served as an example for rapid review of many features that I had studied at more leisure in other ranges. It sufficed to show that physiographic evidence of block faulting may be easily and quickly recognized when it is looked for. It confirmed my opinion that such evidence compares well in logical and compulsory value with the stratigraphic evidence on which the demonstration of faulting is usually dependent. It strengthened my belief in the importance and the possibility of describing all land forms rationally and systematically in view of their evolution.

The description of the Shoshone range in the reports of the 40th Parallel Survey is so closely limited to matters of geological structure — as was natural enough at the time the Survey was made, and the reports were written — that no consideration is given to the physiographic features here discussed. The range is not mentioned in Gilbert's or Russell's reports, or in Spurr's essay. The fuller meaning of my notes, supplemented by the maps and reports of the 40th Parallel Survey, and by the thoughts that accompanied the observations, is as follows: —

The northern ten miles of the Shoshone range in north central Nevada is an east-dipping monocline of Weber quartzite overlaid by basalt (40th Par. Surv., map 4, west half). It is bordered on the north and west by the open alluvial plain through which Humboldt river wanders. From five to ten miles north of the range lies Shoshone mesa, composed of rhyolite covered by basalt, fronting southward in a strong escarpment, and dipping gently northward. The Central Pacific railroad skirts the base of the range for twelve miles along its northern end, giving a good view of part of its western outcropping face, and its northern cross section. The range has every appearance of being a dissected monoclinal

fault block, owing its relief to gradual and long-continued displacement, whose later movements are clearly recorded in the form of its base. Although the observations on which this statement is made were made only from a passing train, they are believed to be fully deserving of credit. It should be understood, however, that they apply only to the northern part of the range. The passage from observation to explanation may be stated as follows: —

The first feature to be noted is the block-like appearance of the mass, especially as indicated by its basal outline. The base line is relatively well defined, of very small irregularity and of moderate curvature; the basal mass is continuous but for the narrow ravines that divide it into full-bodied spurs.

In the second place, attention should be given to the contrast of the heavy mountain mass and the broad piedmont plain. The lower slopes of the mountain are strong; they change rather abruptly into the broad alluvial plain that stretches away unbroken for several miles. The depression, floored by the piedmont plain and drained by Humboldt river, is five or ten miles wide between Shoshone range on the south and Shoshone mesa on the north, and does not give the impression of being a normal trunk valley, eroded in a once continuous rock mass; for if it were of such origin the branch valleys by which the mountain is drained ought to be of correspondingly advanced development with broad-open floors; while as a matter of fact the branch valleys are narrow to their mouths at the mountain base. Moreover, in the neighborhood of Palisade, twenty-five or thirty miles further east, the Humboldt river has what appears to be a perfectly normal valley; a narrow canyon cut in lavas. The broad plain and the narrow canyon cannot both be parts of an undisturbed normally eroded valley; and as the narrow canyon is manifestly of river origin, the broad depression must be otherwise explained.

The depression might at first sight be regarded as a down-warped part of a normal valley, heavily aggraded with alluvium; but this supposition is untenable, because the alluvium does not invade the ravines on the mountain flank as it certainly should if the ravines had been carved with respect to a now-buried trunk valley. Some other origin than erosion must therefore be discovered for the depression alongside of the mountain.

Differential movement or faulting, the only other conceivable origin of the depression — the supposition that the mountain rocks were originally deposited only on their present limited area need not be considered — is not only permissible by its appropriateness to the outline of the

mountain base; it receives strong support from the abundant evidence of the recently continued movement on the fracture by which the depression and the mountain block were originally outlined. The evidence to this end is interesting from its variety and its accordance.

Graded valley floors of moderate width dissect the mountain side, but their floors lie one hundred or two hundred feet above the plain; the valley streams have now entrenched narrow ravines in the valley floors, and thus flow out upon alluvial fans at the mountain base. The spurs between the ravines are of rounded, full-bodied form; they do not taper away on the plain, but are rather sharply cut off by the basal slope of the mountain. The upper surface of the spurs is maturely graded, but their lower slopes are often gashed or "ripped" by little gullies, suggestive of active erosion; the color of the spur slopes is therefore prevailingly lighter than that of the spur tops. Many of the fans are broken by low scarps closely in line with the mountain base; this indicates a continuation of faulting into a very recent period. Some of the fans at the northern end of the western base of the range seem unusually low, as if the plain there had been depressed while the mountain was rising. Taken all together, one can hardly imagine more satisfactory evidence of block faulting.

It should be noted, however, that the higher parts of the mountain seem to have been abundantly dissected since the faulting began. The west-facing scarp of the basalt sheet is now a mile or more back from the west-facing scarp of the underlying strata, but the accordant outlines of the two scarps strongly suggest the original definition of both by the same surface of fracture. Deliberate and detailed study of this range would well repay the observer who could undertake it.

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EXPLANATION OF PLATES.

PLATE 1.

A. The front of the Spanish Wahsatch, looking south. The terminal facets of the spurs are here seen in profile. The Bonneville beach makes a bench at their base, and the beach is broken by a recent fault scarp a little forward from the mountain. The canyon of Spanish fork is in the middle distance, and the Mount Nebo division of the Wahsatch range rises beyond.

B. The front of the Spanish Wahsatch, looking east. The spurs and their terminal facets, separated by sharp-cut ravines, are here seen in full face view. The Bonneville beach is a light line just over the trees of the nearer fields. Plate 1, A, was taken from the vertex of the triangular facet to the right of the mid-base of the northernmost spur.

PLATE 2.

A. An unbroken fan at the base of the Pueblo mountains. A view down the canyon from which this fan is supplied is given in Plate 5, B. Deegan's house is close to the mouth of the canyon. The view is taken looking a little west of north.

B. Cane spring ranch and the Santa Rosa mountains. The ranch lies near the Lahontan shore line on the long slope of waste that is spread forth from the mountain ravines.

PLATE 3.

A. The eastern face of the Pueblo mountains. The rounded spurs shown here contrast with the sharp-edged spurs of the Spanish Wahsatch, Plate 1, B. This part of the range stands between the two canyons shown in Plate 5.

B. The southern end of the Provo Wahsatch. The mountain spurs are terminated by well-defined triangular facets whose bases stand at the level of the Bonneville shore-line. The view is taken looking northeast.

PLATE 4.

A. Rock canyon in the Provo Wahsatch. The walls of the canyon are more rugged than the front slope of the range. The view was taken from the roof of Provo Academy, looking northeast.

B. Slate canyon in the Provo Wahsatch. This repeats the features of the previous view. It was taken from the same point, looking southeast.

PLATE 5.

A. A canyon in the Pueblo range, near Denio. The view is taken from the lateral slope at the canyon mouth, looking up-stream (west). The broken fan at the canyon mouth is shown in Plate 6, A.

B. A canyon in the Pueblo range, near Deegan's. This canyon is three miles south of the one shown in the preceding plate. The view is taken looking eastward to the Alvord valley plain. The fan at the canyon mouth is shown in Plate 1, A.

PLATE 6.

A broken fan in the Pueblo range; front view. This fan is at the mouth of the canyon near Denio shown in Plate 5, A. The direction of the view is northwest.

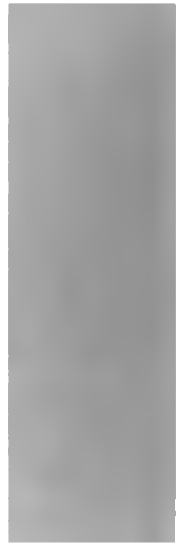
PLATE 7.

A. The Stein mountains, near Andrews. This is part of the east-facing escarpment of the middle division of the range, as seen looking northwest from Miranda's ranch. The base line of the range is here poorly defined.

B. A residual mountain range in southern Utah. This small unnamed range, about forty miles north of St. George, possesses gently sloping spurs, open-mouthed valleys, and an ill-defined base line, in contrast with the Wahsatch and Provo ranges illustrated above.

A. FRONT OF THE SPANISH WAHSATCH, LOOKING SOUTH.

B. FRONT OF THE SPANISH WAHSATCH, LOOKING EAST.



A. UNBROKEN FAN AT THE BASE OF THE PUEBLO MOUNTAINS.

B. CANE SPRING AND THE SANTA ROSA MOUNTAINS.

A. EASTERN FACE OF THE PUEBLO MOUNTAINS.

B. SOUTHERN END OF THE PROVO WAHSATCH.

A. ROCK CANYON IN THE PROVO WAHSATCH.

B. SLATE CANYON IN THE PROVO WAHSATCH.

A. CANYON IN THE PUEBLO RANGE, NEAR DENIO.

B. CANYON IN THE PUEBLO RANGE, NEAR DEEGAN'S.

BROKEN FAN IN THE PUEBLO RANGE.

A. STEIN MOUNTAINS, NEAR ANDREWS.

B. A RESIDUAL MOUNTAIN RANGE IN SOUTHWESTERN UTAH.

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No. 4. — *Postglacial and Interglacial (?) Changes of Level at Cape Ann, Massachusetts.* By R. S. Tarr. *With a Note on the Elevated Beaches.* By J. B. Woodworth.

Nature of the Work. — Investigation upon the recent geology of Cape Ann was begun by me in 1887 in connection with work for the United States Geological Survey under the direction of Professor Shaler. The results obtained during that period have been published in the Ninth Annual Report of the United States Geological Survey (pp. 529–611). Since that time frequent visits to the region have furnished opportunity for further study, attention being specially directed to tracing the evidence of recent elevation along that coast. The discovery of well-defined beaches and other evidences of uplift, first made in 1887, received very distinct support from these later studies, and it is a statement of these additions to the evidence proposed by Professor Shaler that constitutes excuse for this paper.

In the prosecution of the work very material aid has been given by Mr. John L. Gardner, whose interest in the investigation led him to generously undertake the expense of a careful, detailed survey of some of the most pronounced beaches; and the maps which were made for this purpose by Prof. A. E. Burton of the Massachusetts Institute of Technology are used as illustrations in this paper (Plates 2, 3, and 4). The preparation of these maps is a matter of distinct importance, since they place on record the form and elevation of these beaches, which are in danger of speedy destruction because of the encroachment of summer residences upon their sites.

Stripped Areas and Stratified Deposits. — The evidences that the sea has covered the coastal margin of Cape Ann at least up to an elevation of 40 to 60 feet above the present level are very distinct and of several kinds.

In the first place, as clearly stated by Professor Shaler, while the center of Cape Ann is heavily strewn with morainal deposits, the coastal strip is almost clear of such accumulations and is marked by a distinct predominance of bare rock. Above an elevation of from 50 to 60 feet the soil is almost entirely morainic till, more sandy than is common in many regions, but nevertheless distinctly unstratified. Below this ele-

vation, on the other hand, in nearly every case where I have seen a cut in the soil, it is made of stratified materials, sometimes only very roughly assorted, but in many places perfectly stratified.

At the elevation of from 40 to 90 feet there are frequent bare ledges of rock causing some of the unique bits of scenery which have rendered the Cape famous among summer visitors (Plate 5). Below this strip of bare rock are level stretches of stratified material. When the studies were first begun in 1887, the suggestion at once arose that this stretch of bed rock, which so closely resembles the stripped area of granite just above the present high-tide mark, in reality represents a stripped area produced at a time when the waves were working at a higher level and were able to wash the loose soil from the ledges, as they have so effectually done all along the exposed coast of the Cape at the present level.

The resemblance between the upland topography at an elevation of from 40 to 90 feet and the present coast line is in many places clearly defined in the way just described; but, just as along the present coast there are many differences from place to place, in accordance with the location with reference to exposure to waves, or with reference to the nature of the under rock, so at the upper levels there are also variations from place to place. For instance, along the Pigeon Cove coast, one of the most exposed parts of the Cape, the jointing of the granite is of such kind as to furnish sloping layers of rock dipping seaward, much as would be the case if there were a series of sedimentary beds with a seaward dip. The waves along the present coast wash up over the sloping granite for a long distance, and, except in one or two places, the coast is not bordered by beach accumulation. At first the failure to discover evidence of former depression in this part of the coast was considered very puzzling; but as the studies were carried on in more detail, it soon became evident that beaches would probably not have been formed here. Instead, as along the present coast, the granite was completely stripped of all soil, though it is now covered in places with a thin veneer of gravel resulting from the postglacial decay of the bed rock.

On Eastern Point, which forms the eastern boundary of Gloucester Harbor, the bare rock area is much greater than in any other section of the Cape of equal size. Here even the higher hills are washed clear of drift; and in this part of the Cape the raised beaches are very well developed. This is in harmony with what one would expect, for since the ice movement was from the northwest, the southeastern margin of the Cape was first exposed to the waves; and even while the moraine of Cape Ann was being built by an ice stand, Eastern Point, and the east-

ern part of the Cape in general, which were then at a lower level, were open to sea action.

Whether the land at that time stood even lower than the limit indicated by the beaches cannot be positively stated, although the very rocky and bouldery condition of the eastern section of the Cape, including the bear-den moraines, suggests this explanation. An alternate explanation of the rocky eastern section is that while the ice was standing here, the waters formed by its melting, and from the melting of the snows in the spring, were enabled to wash the loose accumulations from the hills of Eastern Point and elsewhere. That is the explanation of similar conditions in Greenland; and, in fact, there is a close resemblance, in a small way, between the bare rock hills of Eastern Point, with the frequent perched boulders, and the rocky surface of the Greenland coast line, which is strewn with boulders perched often in rather unstable positions.

Sand Dunes. — On the island which forms the end of the Cape there are at the present time practically no sand dunes, with the exception of some low ridges just above high tide, developed along two or three of the beaches, especially those on the southeastern side. West of the estuary of Squam " River," however, there is an extensive development of sand dunes supplied from the sand of Coffins' Beach. These dunes had their beginning a little over a century ago, when the forest was stripped away, and are still in process of formation. On the opposite, or eastern side of Squam " River " is a stretch of dunes (Plate 1) extending with considerable continuity from the village of Annisquam to Folly Cove beyond Lanesville, a distance of three and a half miles; but these dunes have long since ceased forming, and there is no evidence of source of supply for them. Instead of being composed of white sand, and supporting only the sparse sand dune vegetation, these dunes (Plate 6) are throughout, from top to bottom, discolored to a yellow through the formation of hydrous oxides of iron formed by the decay of the mica and hornblende bits which constitute a part of the dune sand. These dunes reach to an elevation of from 80 to 100 feet above sea level, and some of the individual hills have a height of fully 25 feet. In all but one of the places where the bottom could be seen, the sand rests upon bed rock with no soil between. The exception mentioned is near the head of Lobster Cove at Annisquam, where the sand rests upon an angular, roughly stratified accumulation of pebbles, clay, and sand resembling the deposits now being made along the coast of this well-enclosed cove. In several places, scattered, well-rounded pebbles were found resting on the granite at the base of the sand.

There can be no question that the sand dunes of this locality have been formed in the past when conditions were very different from those of the present; for now the entire coast line in this region is granite rock without the vestige of a beach to supply the sand. Nor is there any interior supply; it seems to have come from the seaward side. It might, of course, be assumed that when the waves began their work after the ice retreated, they stripped the soil from the rock and formed beaches which have since been destroyed, leaving no evidence of their existence, and that all this happened while the land was at its present elevation.

This explanation seems inadequate for at least two reasons. In the first place, the presence of the rounded pebbles suggests the presence of the sea at higher level; and, in the second place, the present outline of the coast is not of such a form as to lead to the development of beaches. It is altogether too straight a stretch of granite; but if the land were depressed the coast line would become very much more irregular, and sand beaches might well develop in the bays. With the disappearance of the waves from the land through elevation, the beach sands might well have been blown about, forming sand dunes.

While by itself this area of sand dunes, although strongly suggestive, could not be deemed conclusive evidence of former depression of the land, when taken in connection with the other evidences of depression it constitutes a link in the chain of evidence of such importance that it must be considered.

Delta Deposits. — Since there are no large streams on Cape Ann, well-developed deltas would not be expected. Only one perfectly defined delta was found on the Cape. It is located near the road from Gloucester to Rockport, and is best seen where a branch road extends from the one just mentioned down to Good Harbor Beach (F, Plate 1). At this point the delta is bisected by a small stream flowing from the direction of Cape Pond. The crest of the delta is about 50 feet above sea level, and it has a length of about one-half mile, with a width of a quarter of a mile. Along the road to Good Harbor Beach a cut reveals the internal structure of the delta to the depth of 25 feet, showing distinctly cross-bedded sands and gravels dipping seaward and overlain by horizontal surface beds of gravel. The crest is remarkably level, though with a gentle seaward slope; and upon its surface, in several places, are linear indentations, evidently channel ways. It faces away from the ice, and toward the open sea, and therefore there is no reason for considering it a sandplain in an enclosed valley dammed by the ice.

A deposit apparently of the same origin occurs near the mouth of the Alewife brook (K, Plate 1), the outlet of Cape Pond. It is now so badly destroyed by excavations for street grading that the form is not preserved; but before these excavations were made the features of the delta were plainly seen. One feature in connection with this deposit is the presence of abundant boulders of large size, showing that while the water was depositing the layers there was some means — as floating ice — for the transportation of large rock masses. The Alewife brook delta deposit extends up stream for a long distance, the valley being bordered, sometimes on both sides, but more often on only one, by stratified, terrace-like beds. One of these is locally known as the "Sand Pit," and even farther upstream than this, at about the level of the former coast line, is an extensive stretch of level land now for the most part occupied by a swamp. The association of these features with the largest brook on the Cape leads to the belief, when taken in connection with the other evidence, that this is really a delta formed in the sea during a lower stand of the land.

At that part of the delta first described, the Alewife brook turns abruptly at right angles to the north and changes its character from a brook to a tidal stream called Mill "River." A large part of Mill "River" valley bottom is salt marsh; but this is flanked on either side by stratified beds which extend from Riverdale into the city of Gloucester (I J, Plate 1). So much building has been done over a large part of this level, stratified area that one cannot now tell what its original condition was; but in that region, wherever cuts have been made at levels below the 45 foot contour line, they have revealed stratified drift. This region is so enclosed by hills that it is impossible to consider these deposits as beaches, but their uniformity of extent at the former sea level leads to the belief that they are connected in origin with the former sea level. There is now no stream which could have formed such extensive beds of stratified deposit, but it is noteworthy that they are located along the broad north-south depression which, at the present stand of the sea, completely cuts the end of Cape Ann from the mainland, transforming it to an island. While the ice front was building the Cape Ann moraine, water from the melting glacier was doubtless supplied to this valley; and it is also possible that it served as the outlet for a subglacial stream, which would account for the stratified deposits that abound along the valley sides and bottom.

This explanation, which seems the only possible one, would assign to the stratified beds in the neighborhood of the city of Gloucester an origin

similar to that of some sandplains, although the development of surface features is not nearly so typical here as in some of the sandplains near Boston.

If a depression of Cape Ann can be proved to have occurred in post-glacial times to the amount of 40 feet or more, it would be expected that similar proof could be found in other regions near by. I have made no attempt to extend the study beyond Cape Ann, but the suggestion has occurred to me that at least some of the sandplains of eastern Massachusetts, and some of the broadly extended stratified beds near the mouths of large streams, are really delta deposits made when the land stood lower than at present.

Beaches. — In a number of places along the shore, especially the eastern and most exposed shore of the Cape, distinct beaches were found at the elevation indicated by the other stratified deposits described above. It does not seem worth the while to take the space for specific description of many of these beaches, and therefore only three or four of the best will be described.

A very interesting bar, evidently resulting from wave wash, is found near the southern end of Eastern Point on the site of the old government fort (A, Plate **1**). The bar is crescentic in shape and is isolated from higher land. Its crest has an elevation of 50 feet. By itself it would prove nothing, but its elevation, which is the same as that of much better developed beaches near by, indicates that it is of wave origin. The appearance of the area near this bar indicates that there was here either a shoal or else a low island which the waves gradually washed away, leaving a bar on one end. Its position and form are indicated on the map.

Less than a mile to the northeastward from this is a well-developed cusp whose position is marked on the map (B, Plate **1**). It is so well defined that the United States Coast Survey topographers gave to it a special contour, as will be seen on the United States Geological Survey map, which in this place is based upon the Coast Survey map. This beach is one that Professor Burton surveyed for Mr. Gardner to be used in this paper, and the maps made from this survey are reproduced as Plates **2** and **3**. By the maps it will be seen that along the present coast line there is a rocky stretch of coast toward the northeast, succeeded toward the west by a pebble beach which grades into a sand beach on the extreme west. The modern beach reaches an elevation of a little over 14 feet above mean sea level, and behind this is a swamp 5 feet lower. It stands, therefore, as a bar, and its outline is that of a cusp. Almost parallel to

the present beach, and from 500 to 700 feet inland, is another bar reaching an elevation of 41 feet and sloping away from the crest in both directions. It is flanked by a swamp about 15 feet lower than the crest. Its form is distinctly that of a beach, and cuts that have been made in it prove it to be composed of well-stratified materials. The surface is strewn with large water-worn pebbles resembling those of the modern beach. Back toward the northwest, the bar broadens until it reaches the base of some low rocky hills (Plate **5**) which have the appearance of having been stripped of their drift cover. The base of this series of rocky hills is from 42 to 47 feet above mean tide level.

If the land could now sink far enough to permit the waves to wash the base of these rocky hills, all the land at present to the seaward of them would be below the water, although some places, especially at the eastern end of the bar, would reach almost to the high-water mark. Assuming that nothing had been stripped from any of the hills, the condition would then be a coast line at the western margin of the bar and a series of shallows at the eastern margin. The prevailing direction of effective waves approaching such a coast then, as now, would be from the northeast. Breaking upon the shoals of the eastern end they would remove whatever loose fragments were available, and drive them toward the southwest. The loose fragments derived from the western margin would be driven onward toward the south and, as the waves advanced into this more or less completely enclosed arm of the sea, one would expect them to build a crescent-shaped beach similar to the crescent beaches which are so common along the coast. Indeed, the beach at the present sea level (described above) is such a crescent bar forming a barrier which has cut off Niles Pond from the sea.

Another elevated beach, in some respects resembling the one just described, is found west of High Pebble Beach (D, Plate **1**). It faces the northeast, and skirts a line of rocky hills on the north and south sides, while on the west side it stretches across as a bar (Plate **7**) from the hills on one side to those on the other. Its form is well shown on the accompanying map, also made for Mr. Gardner by Professor Burton (Plate **4**, B). The crest of this bar is 52 feet above the present tide level. The fact that it is higher than the bar just described is doubtless due to its exposure. In the case of the beach first described (Plates **2** and **3**), the waves from the northeast must have been greatly interfered with by shallows, and possibly at first by low islands; but the beach back of High Pebble Beach was exposed to the full force of the northeast waves. Its form is well shown not only on the map (Plate **4**), but also in the

photograph (Plate 7). Like the other beaches, this one is composed of well-assorted stratified materials with many distinctly rounded pebbles. A photograph of a cut in this beach is reproduced as Plate 8.

About three-quarters of a mile north of this beach, and back of the Moorlands Hotel is further evidence of the depression of the land. There is a rock cave flanked at the base by a number of disrupted boulders, the whole region being closely like the present condition at Bass Rocks, where the sea is at present beating and rending similar masses of rock from the ledges.

A half mile north of this, along the electric car line from Gloucester to Good Harbor Beach, at the base of the hill which lies to the south of the road, is an accumulation of stratified material (E, Plate 1). While not exactly like a beach, similar to those at present existing on the coast, it does resemble what one would expect to be formed by rapid wave work, in a protected bay along a drift-covered coast.

There are numerous other stratified deposits along this level and below it. One of the best elevated beaches along the coast occurs just west of Whale Cove, near Turk's Head Inn (G, Plate 1). This is fully described in the accompanying paper by Professor Woodworth.

Absence of Fossils. — One of the reasons for not having previously published the evidence of former depression of the land in Cape Ann has been the hope, long deferred, that fossils might be found in some of the deposits. I have searched with care in every cut that I have seen on Cape Ann in the last sixteen years, and have never found a single fossil in the deposits of postglacial age. With the abundance of such fossils in the beaches further north, as in Baffin Land, this absence of organic remains seems difficult to explain, and for a long time led me to question whether some other explanation of the phenomena at Cape Ann could not be suggested; but the evidence of depression seems so perfect that, notwithstanding the absence of fossils, I feel convinced; and I am obliged to assume that their absence is to be accounted for by adverse conditions, such as the short stand of the land and the coldness and muddiness of the water. It must be confessed that when one finds an abundance of animal life at the very base of the Greenland glacier, in such a position as to be thrown to the surface when icebergs break away from the glacier, this explanation seems weak. However, the deposits on Cape Ann were made at the edge of a rapidly retreating ice front, and marine life may not have advanced this far while the land was lower.

It is, of course, possible that fossils exist here, but have not yet been detected. I have been told of the former discovery of fossils in a num-

ber of places, but evidence of this kind is of little value; and each time that I have looked where they were once found, it has been discovered that they no longer occurred there.

Summary. — While a single one of the evidences set forth in this paper might not be considered proof of depression of Cape Ann in post-glacial times, the accumulation of evidence from several directions is such as to make the conclusion necessary that this part of the coast has been depressed to a level at least 40 to 60 feet lower than the present.

Summarizing this evidence, it may be said to consist first and most prominently of a number of well-defined beaches at a level of from 35 to 60 feet. At about the same elevation, over most of the Cape, stratified drift is found wherever cuts are made, and some of this is evidently delta deposit. While much of the stratified material cannot be positively associated with wave action, or with the action of streams at present existing, its occurrence below a certain level, while above that level there is much unstratified drift, and almost no stratified material, is suggestive. That these deposits do not more frequently assume the forms of the present coastal deposits is readily understood when we consider the brief duration of the lower stand of the land in comparison with the present long stand.

The extinct sand dunes of the Lanesville region, occurring where there is now no apparent supply of sand, and long since having ceased forming, is also suggestive of a lower stand of the land, especially since well-rounded pebbles are found beneath this sand in some places.

Interglacial (?) Beds. — In 1866 Professor Shaler announced[1] the discovery of fossils from a deposit of stratified drift on Cape Ann not far from the Pavilion beach. His list of fossils is as follows: —

"LEDA. Two specimens.
MODIOLA DISCREPANS Say. Several specimens.
MYA TRUNCATA Linn. ?. Several specimens.
MESODESMA ARCTATA ?. Very doubtful.
NUCULA SAPOTILLA?.
PANOPEA ARCTICA Gould?.
SAXICAVA DISTORTA Say.
Five or six specimens of Lamellibranchiata not identified.
Crustacean remains, plentiful but very fragmentary."

While engaged on the work at Cape Ann with Professor Shaler, both he and I tried to rediscover this locality, but without success. In 1897,

[1] Proceedings Boston Soc. Nat. Hist., 1866, Vol. II., pp. 27–30.

however, while extensive excavations were being made at Stage Fort (L, Plate 1) on the western end of Pavilion Beach I found these beds revealed in such remarkably perfect condition as to show not only the fossil contents, but many other facts as well. Some of the features revealed there are very well illustrated in the figures (Plates 9-13). It will be noticed that there are two sets of beds, one very much contorted and stratified, the other overlying these unconformably. The latter deposit is nothing more than the ordinary till of the region, being somewhat sandy and very bouldery, as is all of that upon Cape Ann. It rests upon the grooved and eroded under-beds with a very distinct unconformity.

The strata below are folded in such a way as to be even contorted in places, and there is thrust-faulting. These beds are for the most part clays and sandy clays entirely unconsolidated, although some layers are very compact. One or two of the layers are pebbly, especially a layer at the base, which is shown in Plate 12. Scattered through the contorted layers are numerous angular boulders, some of them shown in the pictures. In some cases these reach a weight of one to two tons. Some of them are foreign to the region, like the erratics which occur on various parts of the Cape.

The stratification proves sedimentation in water, and the scattered boulders prove a transporting power different from that which brought and deposited the layers of sand and clay. They must have been carried by floating ice, having previously been brought from a distance. The suggestion occurs at once that these were brought during the first advance of the glacier and deposited in the sea at a time when this part of the land was below sea level. The ice of the second advance of the glacier overrode these interglacial (?) deposits and failed to remove them all, doubtless disturbing their position and causing the intense contortion noticed, and at the same time placing upon the surface the veneer of till.

Deposit below sea level is also proved by the presence of the fossils mentioned by Professor Shaler and those that I collected. The coldness of the water is also proved by these, suggesting the possibility of floating ice in the neighborhood. While considerable numbers of fossils were obtained from the fossil-bearing beds of the series, their imperfect state of preservation rendered transportation so difficult that, when I came to unpack them, I found most of them crumbled to bits; and upon the next visit the abundant fossil-bearing layer was no longer exposed; but among those which were sufficiently well preserved for identification two, also found by Professor Shaler, were characteristic of cold water. One,

Yoldia siliqua, is also found fossil in the clays near Portland and Montreal, and occurs in the present waters of the Arctic, as at Beechey's Island and Greenland. The other, *Aphrodite groenlandica*, is a distinctly northern form.[1]

The fossil-bearing layer is from 15 to 20 feet above mean sea level, and the interglacial (?) beds extend fully 10 feet higher, indicating subsidence during this interglacial (?) time fully 30 feet below the present level. How much has been removed by erosion from the top of these beds can not be stated, but it is evident that not a little has been carried off. The clayey layers also suggest a subsidence sufficient to remove the area from the immediate neighborhood of the rocky coast; and the presence of boulders, some of which are fully two tons in weight, suggest sufficient depth for large masses of ice to float. It seems difficult to account for these transported fragments in water having a depth less than a hundred feet.

Other deposits of the same kind may be expected in different parts of the Cape, and at levels considerably above this; but it is hardly probable that such extensive deposits will be found elsewhere, for those at Stage Fort have a peculiarly favorable situation for preservation, being situated on the lee side of a high range of hills which has protected them from removal. It is unfortunate that neither the wave action nor the excavations that were made reveal the base of these beds; and, therefore, it is not possible to state with certainty that these are interglacial rather than immediately preglacial beds, although there is, in fact, little reason to doubt their interglacial age.

Note on the Elevated Beaches of Cape Ann, Mass.

BY J. B. WOODWORTH.

A few years ago, under Professor Tarr's guidance, I saw the elevated beaches which are described in his paper as lying on the seaward face of Eastern Point, Cape Ann. The notes which are here appended to his paper are therefore a direct outgrowth of his own work on these elevated beaches. The discussion concerning the extension of the marine limit southward is, however, made independently.

In the fall of 1902, in the company of Mr. J. W. Goldthwait of the Geological Department of Harvard University, I made a visit to Rockport and sought for shore lines from the crest of Pigeon Hill at the cove

[1] I am indebted to Prof. G. D. Harris of Cornell University for the identification of these fossils.

of that name, down to the existing sea level, and thence southward along the coast between Gap Head and Emerson Point. The results obtained, since they confirm and somewhat extend Professor Tarr's observation in the same field in regard to the elevation of the beaches are here given, without, however, the precise elevations which it is hoped later to obtain, by levelling, upon the marine limit at Rockport.

Pigeon Hill is a drumlin rising from an almost driftless area of granitic rocks. The hill was selected as a point of beginning the search for the marine limit, for the reason that if this hill failed to show beaches it seemed fair to conclude that the upper marine limit did not rise above the 100 foot contour-line which encircles the hill. The eastern and northern base of this drumlin is outlined by the 80 foot contour line, its western and southern base approximately by the 100 foot contour line. The northern and eastern slopes of this hill, which would have been exposed to heavy waves from the sea, show no scarps or lines of water action above the 100 foot line. On the southwest slope of the hill, there is a marked terrace between 140 and 145 feet, outer and inner edges respectively, by aneroid measurements. This terrace, however, lacks horizontality; it rises either way toward the middle of the side of the hill. From its inner edge rises a healed scarp which, together with the terrace, indicates an alteration of the original lenticular contour of the drumlin. The non-horizontality of the terrace, and the failure of built margins in the form of gravel or sand bars, relegates the terrace to the group of little understood forms dependent on either glacial erosion or glacial stream action taking place during the disappearance of the ice-sheet from the vicinity. It certainly does not appear to the writer that the criteria of wave action are exhibited in this case.

All along the shore, at least from 80 to 90 feet downward, there occur, bordering and between rock cliffs, sloping deposits of sand overlaid by coarse rubble, the ensemble of which is not that of glacial drift, but rather that of deposits making along a rocky coast beneath the water level. These deposits were noted and similarly interpreted by Shaler and Tarr in the report on the geology of Cape Ann published some years ago.[1]

Elevated Beach and Bar at Whale Cove. — The most perfectly formed and highest beach I have seen on Cape Ann is that noted by Professor Tarr, as lying immediately back of Whale Cove, between the shore and the public road. Traversing this portion of the coast from north to south, one comes, on approaching the vicinity of Whale Cove, to a gently

[1] N. S. Shaler: The Geology of Cape Ann. 9th Report of the Director of the U. S. Geological Survey, 1889, p. 573.

shelving flat south of a region of bare rock knobs. This flat ends on its inner margin against a boulder wall of a weak morainal appearance. The flat is strewn with numerous boulders, but where the sod is turned up water-worn stones appear. The upper inner limit of the beach flat according to the contoured map is about 80 feet above the present sea level, but aneroid readings, made at the time of my first visit and later, indicate a lower level of about 65 feet.

South of this place, and retreating inland somewhat from the boulder line just described, is a well-formed bar with level top thrown southward across a slight depression extending landward between bare rocky knobs west of the road. The bar at its southern end is trenched by a small wet-weather brooklet draining the back-bay area behind the bar. The materials of the bar, as shown in a small pit, are rudely assorted water-worn cobbles, gravel, and sand closely resembling glacial stream detritus.

This bar is slightly concave toward Whale Cove. From its crest the ancient beach slopes away in a graceful, saucer-shaped surface at an angle of about 4 degrees to a low bluff of underwater sands 32 feet high bordering Whale Cove.

The bar is composed of water-worn gravel with occasionally larger stones. A section in it is exposed at the breach above mentioned. The elevation of the crest, so far as can be judged from the contours of the map, is about 90 feet, but the bar itself is not clearly indicated on the map with 20 feet contour intervals. Aneroid readings by myself and Locke, hand-level determinations by Mr. Laurence La Forge, U. S. G. S., gave 78 and 77 feet respectively above mean tide level.

A few boulders occasion the outer slope from the crest of the bar down to the bluff on the shore of Whale Cove, and much water-worn gravel appears everywhere at the surface in the upper part of the slope. Lower down over the underwater sands a rubbly layer occurs which is well exposed at the summit-line of the bluff. The finely stratified sands in this bluff have as yet afforded no fossils.

Farther south weak gravel bars, stretching amid rock knobs, occur about the 90 foot line in the manner described by Professor Tarr near Turk's Head Inn. Back of Emerson Point on the southern slope of the southward projecting ridge next the shore, two small spits of gravel occur between 60 and 80 feet, according to the contours of the map. These occurrences, as well as the bar at Whale Cove, indicate the southward drift of the shore material.

The evidence of strong wave action as high as 80 feet above the present sea level on this part of the coast of Cape Ann, considered in connec-

tion with the occurrences of an elevated sea-floor already described by Stone and others on the coast of Maine where marine fossils have been found above the latest glacial drift, makes it difficult, it seems to me, to escape the conclusion that marine action rather than glacial lake waters was also concerned at Cape Ann in the making of the beaches described by Professor Tarr and myself. In a paper now in preparation, I purpose to show that in the southern part of Massachusetts the last ice-sheet existed longer, along and off the coast, than it did on the mainland west of Cape Cod bay, thus allowing the formation and temporary existence of what may be termed proglacial lakes, or bodies of fresh-water, held in front of the ice by a glacier-dam crossing the mouths of valleys, already freed from ice; such a body of water as Professor Crosby has claimed, may have existed in Boston harbor, and even northward along the coast. The fetch of the waves from the northeast necessary to produce the long shore drift observed at Whale Cove on Cape Ann, however, is quite beyond the possibilities of any contemporaneous glacial lake which the facts discovered in the Cape Cod district would warrant.

EXPLANATION OF PLATES.

PLATE 1.

Map of Cape Ann. A, bar on the site of old government fort; B, bar mapped in Plates 2 and 3; C, planed-off island with rim of beach; D, Beach represented in Plates 7 and 8; E, stratified drift indicating wave action; F, Delta; G, Whale Cove deposits; H, dunes; I, J, K, stratified deposits in Mill River valley; L, Stage Fort, till-covered fossiliferous (interglacial (?)) beds.

PLATE 2.

Contour map of elevated (40 foot) V-shaped bar at Eastern Point, B, Plate 1.

PLATE 3.

Contour map of the beach (B) represented on Plate 2.

PLATE 4.

Beach (B) at Eastern Point (Plate 1, D), connecting bare rock hills R, R.

PLATE 5.

Bare rock ledge (wave stripped?) at Eastern Point, looking from the beach, Plates 2 and 3. Photograph by J. L. Gardner.

PLATE 6.

Open oak forest on the extinct sand dune area of Lanesville. (Locality H on Plate 1.)

PLATE 7.

Crest of the beach, BB, Plate 4. The low rock hills showing on the extreme left, and the swamp in front appearing in the foreground. View from locality V, Plate 4. Photograph by J. L. Gardner.

PLATE 8.

Cut in the beach at locality C, Plate 4. Photograph by J. L. Gardner.

PLATE 9.

The interglacial (?) beds at Stage Fort, Gloucester, showing the crumpled strata. Photograph by J. L. Gardner.

PLATE 10.

Unconformity between the till and the crumpled interglacial (?) beds. Photograph by J. L. Gardner.

PLATE 11.

Crumpling and thrust-faulting in the interglacial (?) beds at Stage Fort. Photograph by J. L. Gardner.

PLATE 12.

Gravel layer (at left of cut) beneath the interglacial (?) clays; till above. Photograph by J. L. Gardner.

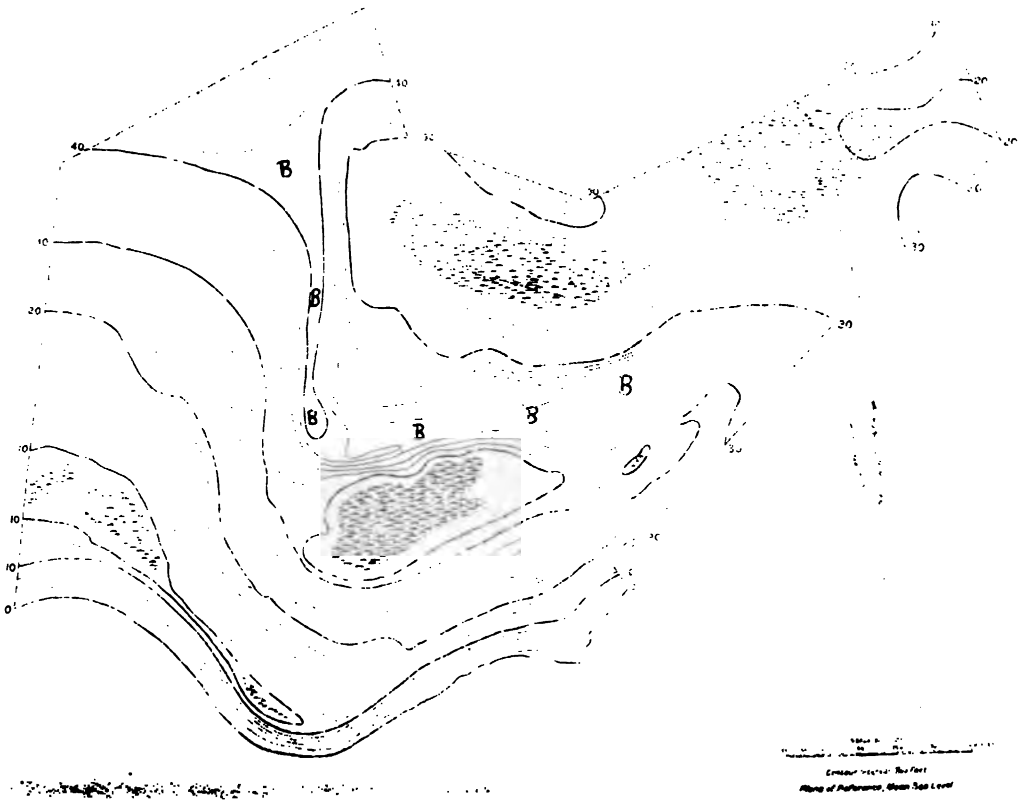
PLATE 13.

Large boulders in the interglacial (?) beds. The till has been removed from the top. Photograph by J. L. Gardner.

CONTOUR MAP OF ELEVATED (40 FOOT) V-SHAPED BAR AT EASTERN POINT. (B, PL. 1).

HELIOTYPE CO., BOSTON.

CONTOUR MAP OF ELEVATED (40 FOOT) V-SHAPED BAR AT EASTERN POINT (B. Pl. 1)



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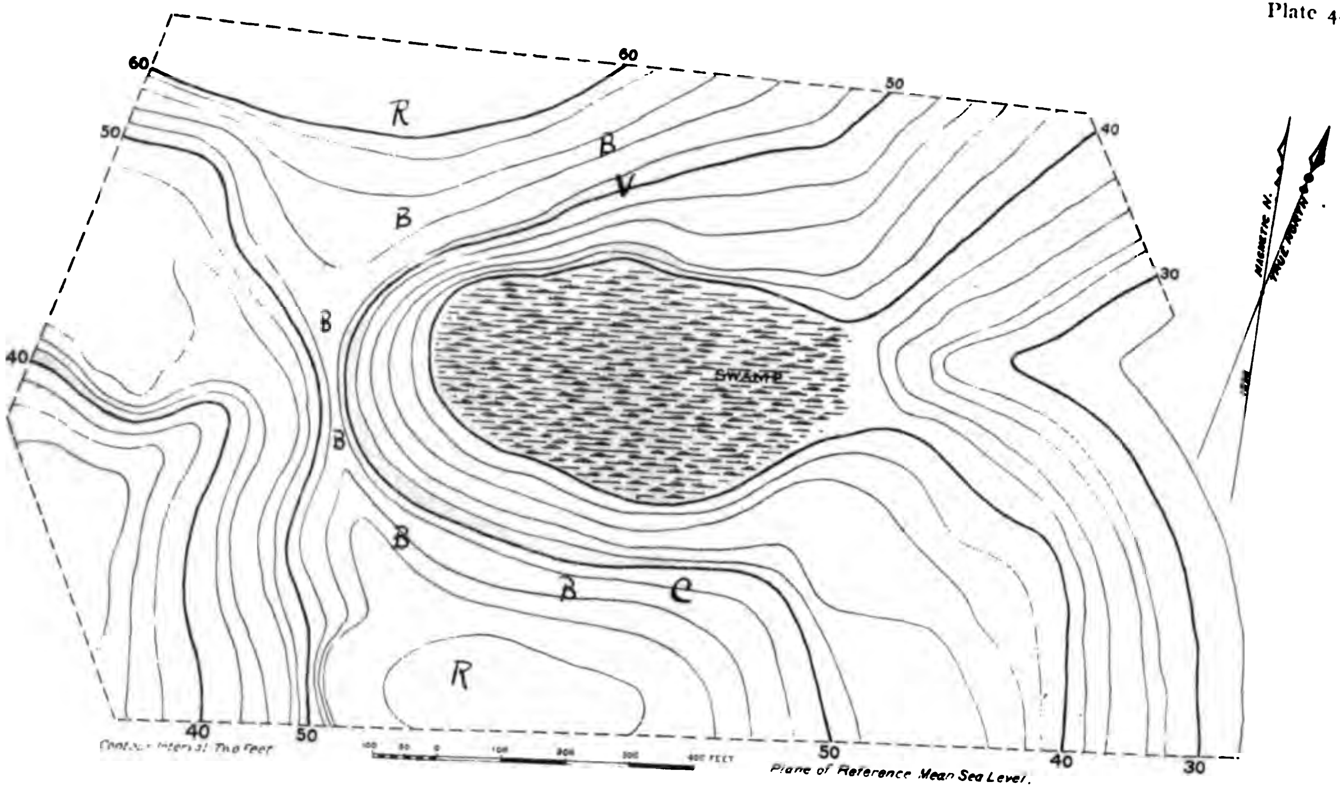
CONTOUR MAP OF THE BEACH (B) REPRESENTED ON PLATE 2.



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THE ELEVATED BEACH (B B ETC.) AT EASTERN POINT (PL. 1, D), CONNECTING THE BARE ROCK HILLS (R, R,).

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

BARE ROCK LEDGE, WAVE-STRIPPED(?) AT EASTERN POINT, LOOKING FROM THE BEACH (PL. 2 AND 3).

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OPEN OAK FOREST IN THE EXTINCT SAND DUNE AREA OF LANESVILLE, MASS. (H IN PL. 1.)

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

CREST OF THE BEACH (B, B, IN PL. 4), THE LOW ROCK HILLS SHOWING ON THE EXTREME LEFT

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

CUT IN THE ELEVATED BEACH (AT C. PL. 4).

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

THE INTERGLACIAL (?) BEDS AT STAGE FORT, GLOUCESTER, SHOWING THE CRUMPLED STRATA.

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

UNCONFORMITY BETWEEN THE TILL AND THE CRUMPLED INTERGLACIAL (?) BEDS

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

CRUMPLING AND THRUST-FAULTING IN THE INTERGLACIAL(?) BEDS AT STAGE FORT, GLOUCESTER HARBOR.

Plate 12.

GRAPH BY J. L. GARDNER.

GRAVEL LAYER (AT LEFT END OF CUT) BENEATH THE INTERGLACIAL (?) CLAYS

STAGE FORT, GLOUCEST

HELIOTYPE CO., BOST

PHOTOGRAPH BY J. L. GARDNER. HELIOTYPE CO., BOSTON.

LARGE BOULDERS IN THE INTERGLACIAL(?) BEDS. THE TILL HAS BEEN REMOVED FROM THE TOP. GLOUCESTER HARBOR, MASS.

Bulletin of the Museum of Comparative Zoölogy

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THE HURRICANE FAULT IN THE TOQUEVILLE DISTRICT, UTAH.

BY ELLSWORTH HUNTINGTON AND JAMES WALTER GOLDTHWAIT.

WITH SEVEN PLATES.

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No. 5. — *The Hurricane Fault in the Toquerville District, Utah.* By ELLSWORTH HUNTINGTON and JAMES WALTER GOLDTHWAIT.

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Introduction.

THE district around Toquerville, in the southwestern corner of Utah, is one which offers much for geological study. In a recent number of this Bulletin Professor W. M. Davis of Harvard University calls attention to the problems seen at Toquerville, more particularly to those which concern the northward extension and the disputed age of the great Hurricane fault (*h*, p. 147). A closer acquaintance with these problems was made when, in the summer of 1902, the writers had the opportunity to visit the Toquerville district under the guidance of Professor Davis, and to spend a few weeks there in geological field work.

The course which our party took, and the dates at which we touched certain points in the plateau country have already been outlined in a paper by Professor Davis (*d*, pp. 2, 3). The wagon route led southward from the terminus of the railroad at Marysvale up the Sevier valley, to the divide between the Great basin and the Colorado river. Thence we moved on, following Kanab creek from its headwaters to the town of Kanab, and passing in succession the great series of broad terraces and stupendous cliffs which descend step by step to the Colorado river, one hundred miles away. In this series of steps we saw consecutively the pink Tertiary cliffs, the brown Cretaceous ridges and hills, the snow-white "Jurassic" escarpment, and lastly the blazing "Vermilion" cliffs and the outlying "Chocolate" cliffs of Kanab. From Kanab we journeyed on horseback across the desert platform of Carboniferous limestone to the Grand canyon, at Mount Trumbull, — a place almost never visited by sight-seers and rarely by scientific travellers. Thence, after two days on the esplanade halfway down the canyon, we rode northward nearly parallel to the Hurricane fault and a few miles east of the "Ledge," to the Virgin river at Rockville. Just above the village, near the Temples of the Virgin, at Zion, we saw the slit-like cleft which the river has cut down two thousand feet through the massive red and white sandstone. From here it was but a short day's trip down the canyon to Toquerville, where we made our headquarters during the three weeks in which we were studying and mapping the surrounding region. At the end of a week Professor Davis went on to Nevada, to study there some of the ranges of the Great basin. After the third week one of the writers returned to Salt Lake city, while the other spent two weeks visiting the Colob plateau, the Grand Wash, and the lower end of the Colorado canyon.

The Toquerville district is one where the whole aspect of the country is as varied as its geologic structure. The town is situated at the base of the Hurricane ledge, a high steep escarpment which marks the course of the Hurricane fault and delimits the great plateau region of the east from the broken Basin Range region on the west. The Hurricane ledge proper, running northward from the Colorado river, decreases in height a few miles southeast of Toquerville, and finally, very near the town, dies out; a short distance northwest, however, a new escarpment, locally called Bellevue ridge, continues north nearly in line with the Hurricane. Between the point where the Hurricane dies out and the Bellevue ridge begins is Toquer hill, a connecting link with anticlinal structure. From the top of this hill, just above the town, one looks

eastward across the broad plateau country, where prevailing horizontality of surface is not weakened but rather strengthened by the long mesas and terraces with their steep fronts, which display the bare horizontal rock structure with all the emphasis that color can give. On the north-

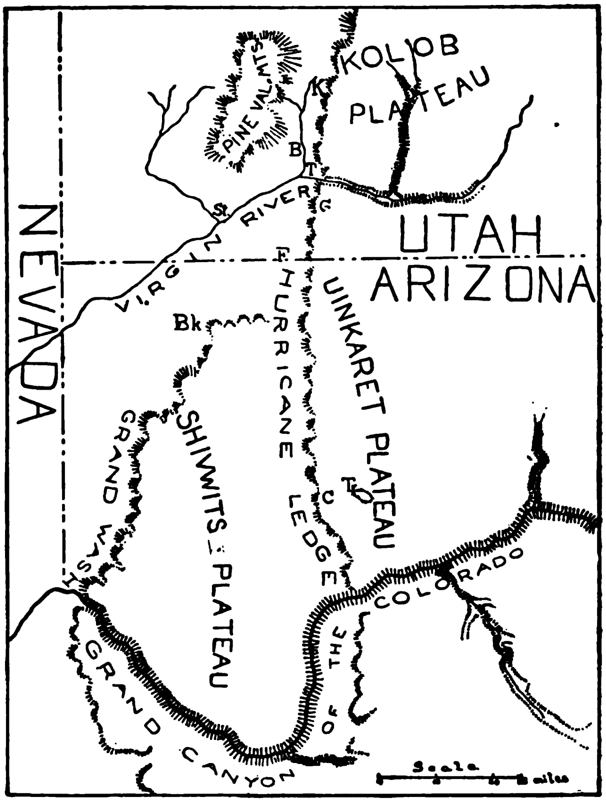


FIGURE 1.

Sketch-map of part of the region traversed by the Hurricane fault. (From Journal of Geology.) K = Kanarra; B = Bellevue; T = Toquerville; G = Gould's ranch; St = St. George; F = Fort Pierce; Bk = Black Rock spring; Tr = Mt. Trumbull; C = Coal spring.

east is the lofty Colob plateau, too far distant to distinguish the smoothly graded slopes of its mature low-mountainous topography; but its conspicuous southwestern flank faces the observer, — a lofty ragged cliff front of red sandstone, the western end of the Vermilion cliff.

The step down from this red-rimmed plateau to the Aubrey platform is broken by an intermediate platform and big flat topped mesas of gayly colored shales capped by a resistant conglomerate bed. Beyond them stretches the vast Aubrey platform. Thus, as one looks eastward towards the plateau country, the impression is uniform horizontality. Turning about towards the west, one sees a different country. Instead of the flat plateaus there are low hills of irregular form, and mountain ranges beyond. To the northeast rise the smooth slopes of the Pine Valley mountains, generally subdued in form though already somewhat scarred by recently revived activity of erosion. Between the range and Toquer hill lie foot-hills, whose irregularity in arrangement of colors indicates a rock structure complicated by folding, in contrast to the regularity of color so noticeable in the plateaus to the east. Towards the southwest the view is limited again by the hills about St. George. In the foreground a lowland stretches from north to south, along the base of the Hurricane-Bellevue cliff front. Near this escarpment the lowland is generally flat and is partly buried under lavas, but here and there black basaltic cones show the sources from which these lavas spread out. Northwest of Toquerville two broad alluvial fans stretch out from the Pine Valley range over the lowland, and these, with the lava sheets, conceal the rock structure over a considerable area.

Such, in outline, is the appearance of the district in which we worked. Our main interest lay in the history of the Hurricane fault, and its bearing upon the broader history of the whole plateau region on its eastern side. Of equal interest was the study of its neighbor, the Grand Wash fault, and it is to the evidence along these two fault lines that we wish to direct especial attention. It seems wise, however, before taking up the main theme — the Tertiary history of the region — to consider briefly the earlier history, chiefly Mesozoic.

The Rock Series.

The question of the subdivision of the rock series into formations has always been puzzling. Newberry, Powell, Gilbert, and Howell contributed much towards an understanding of the stratigraphy of the plateau region; but the scarcity of characteristic fossils made it impossible to divide the series satisfactorily into formations on a paleontologic basis. In his elaboration of the work of these men, however, Dutton has sought, both by direct fossil evidence and by rather doubtful correlations with strata in neighboring provinces, to identify several formations as

representatives of definite geological periods. For instance, the time-names "Permian," "Trias," and "Jura," which suggest that the geological ages of the formations are well known, are applied by Dutton to formations whose exact ages are still in dispute. Since, therefore, we do not feel ready to accept Dutton's names for the doubtful members of the

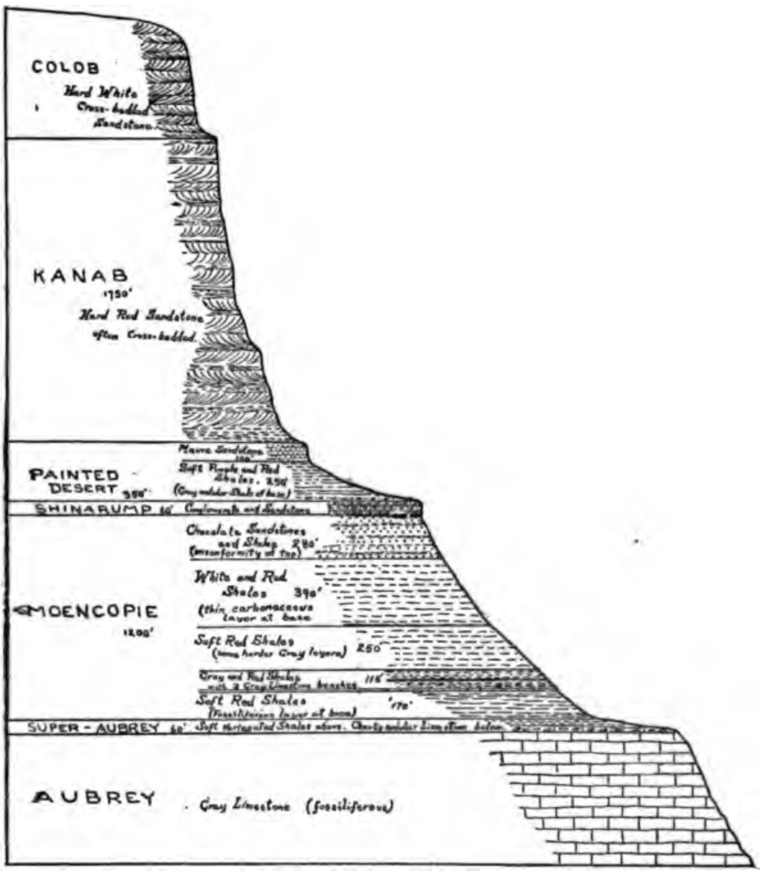


FIGURE 2.

Diagrammatic cross-section of the rock series, as exposed along Le Verkin canyon, between Toquerville and Colob.

rock series, we shall follow the present method of the United States Geological Survey, by using only local names, that have no time significance. In an earlier paper on the Toquerville district (p. 48) we used

the names "Verkin," "Kanab," and "Colob" in place of Dutton's "Permian," "Triassic," and "Jurassic." Since this paper was written, we have learned that Ward had already given the name "Moencopie" to the "Permian" or "Verkin" shales, and had used "Painted Desert" in a somewhat indefinite way for shales of the "Lower Triassic" or "Lower Kanab." In recognition of the priority of Ward's names, we shall discard the term "Verkin" in favor of "Moencopie," and use "Painted Desert" for the soft sandy "Triassic" shales, restricting "Kanab" to the overlying hard red sandstone. "Colob" will apply, as before, to the cross-bedded white sandstone, — the "Jurassic" of Dutton.

The names Colob, Kanab, Painted Desert, Shinarump, Moencopie, and Aubrey apply to single groups of strata that are perfectly distinct from the other groups, not only in structure but also in outward appearance. Each formation has its characteristic color or group of colors, and under erosion assumes forms peculiar to itself.

The colors of the rocks among the plateaus are a revelation to one who has seen only the neutral shades of the ledges in a region of granite gneisses and schists, or the soil-covered outcrops of a forested region. In the lofty buttes and bare rock-walls of the plateau country, one sees a most astonishing display of color, ranging from dull neutral shades of gray and brown on the one hand to delicate pink, rich chocolate, intense brick-red, or pure white, on the other.

Wherever the color changes, in passing from one formation to the next, a complete change in the texture and structure of the rock results in an equally definite change in the shapes developed by erosion. A formation of soft shales may weather down into a long slope, passing below into a flat sandstone shelf that ends sharply in a sandstone cliff. Looking across the canyon of the Virgin river at Rockville, for example, the observer sees a terrace of brightly colored Moencopie shales beneath a dun-colored Shinarump cap, while beyond the hard platform of the latter, and above it, rise gigantic towers and cliffs of a sandstone that looks fairly red-hot.

A few words about each of these formations will serve to give an idea as to the way each looks in the field.

The Aubrey formation, in the Toquerville district, consists of a rather massive gray limestone, capped by a series of colored shales. The limestone resists erosion with much strength. Where it has been cut by the recent Hurricane fault, it stands up as a steep ragged wall. All along the face of the Hurricane its structure shows plainly, even at a

distance, in well-defined lines of light and shade that mark the hard beds from the soft. Every sag in the beds shows itself in a curved line. East of the fault scarp, the Aubrey stretches away as a broad platform, which for miles has been swept clean of the overlying Moencopie shales. It extends from Toquerville clear to the Grand canyon, — a vast yellow dust-covered plain, thinly drained by dry-washes, with here and there a low limestone ridge, a black basaltic cone, or a highly colored Moencopie mesa.

The Moencopie shales, when protected by the strong Shinarump cap, stand up in broad ragged mesas that are remarkable for both color and sculpture. From the top of one of these tables to the plain at its base, the bare slopes descend very steeply, with an occasional narrow bench, limited by a cliff, where a harder member asserts its strength. Seen from a distance, the alternating horizontal bands of chocolate, gray, lavender, and red stand out with ribbon-like uniformity and distinctness. In contour these tables are very irregular, with long headlands and re-entrants, down the slopes of which are cut innumerable gullies and ravines, systematically placed, so as to form a minute pattern of tapering, branching, and sprawling spurs, that give the impression of a conventional design. Where the shales have lost their conglomerate cap, however, they have either been dissected into a choppy bad-land topography of gullies and ridges, or, as is more often the case, they have melted away into broad, gently sloping grade plains, which stretch out from the escarpment for miles, until at last they merge into the Aubrey platform.

In sharp contrast to the weak Moencopie shales below and the soft Painted Desert shales above, the Shinarump stands out firmly as a bench and cliff maker. In the eastern part of our area, among the plateaus, it forms the flat top of the "Permian" terrace, and its outlying tables. Not uncommonly its edge projects out over the soft shales beneath, like an ornamental moulding. Often, where it is the uppermost member remaining, its top is flat and clean; but where it merely flanks the bold Kanab escarpment, its platform is banked by landslides from above. This is well shown at Rockville, near the Virgin river, where the waste of the shales is particularly rapid (Plate 4 B).

Where the strata have been folded, the Shinarump again is conspicuous. Between Toquerville and St. George, where a great plunging anticline has been unroofed by erosion, the conglomerate forms a cigar-

shaped hill, splitting at its southern end so as to surround a long amphitheatre (Plate 2 B).

In Bellevue ridge, where the series from Aubrey to Kanab are tipped up rather steeply with an eastward dip, the Shinarump forms a sharp monoclinal ridge or cuesta (see Fig. 3). We climbed this ridge near Dry canyon. From the base of the Hurricane, up through the super-Aubrey and Moencopie formations, the general slope was never far from thirty degrees, though it was broken occasionally by minor ridges and hollows, where harder members of the Moencopie showed their edges or softer ones had worn away. Toward the top of the shales, however, the slope became steeper and more difficult to climb, until on reaching the

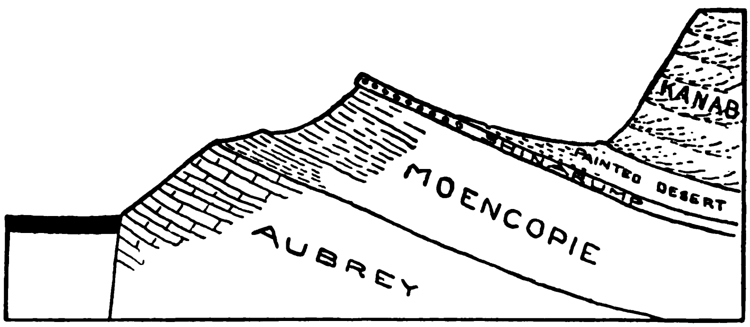


FIGURE 3.
Bellevue ridge near Dry canyon.

Shinarump we found a high cliff that could be scaled only in a few places. Along the greater part of this Shinarump edge, the hard conglomerate projected out over the shale talus, showing how active was the sapping process beneath it. Eastward from the crest there was a long back-slope, down the top of the conglomerate, to a longitudinal valley that had been worn out on the overlying sandy shales.

The Painted Desert formation is a series of shales, elsewhere chiefly clay-shales, but in the Toquerville district more sandy. Although varied in color, they are uniformly weak. Along the Vermilion cliffs, and particularly in the canyons, where revived erosion is most active, the rapid retreat of the shales has induced a general undermining of the overlying hard Kanab sandstone, giving a hummocky landslide topography that is quite different from any other surface form in the region.

At the top of the Painted Desert series, as we have limited it, and at the base of the Kanab, there is a thick sandstone member, of a lavender or mauve color, and of such hardness that it often forms a bench above the shales, after the manner of the Shinarump, though hardly so conspicuously. In Plate 1 A this bench-maker can be seen, near the base of the lofty Temples of the Virgin. Plate 2 A shows it again, this time at Dry canyon, where as a result of tilting it forms a cuesta parallel to the Shinarump ridge, and just east of it.

Above the mauve sandstone, at the base of the Kanab, is a thin series of weak beds, whose non-resistance permits the development of the platform beneath; then comes about seventeen hundred feet of uniformly hard brick-red sandstone, occasionally cross-bedded. It is the unusual thickness and massiveness of this hard sandstone formation that makes it the greatest cliff-builder in the region. As the northwestern portion of the Vermilion cliffs, it runs just outside the limits of our map; for although at Rockville its imposing front trends towards Toquerville, it turns rather sharply, a few miles east of LeVerkin creek, and runs northwest to Colob. The architecture of the Kanab is massive and grand. Lofty though the red cliffs really are, their height is even exaggerated, as a result of prominent vertical jointing, by deep rifts which cut the cliffs from top to bottom. Below, the rifts show as sharp upright slits through the rock, but at the top they widen out into ragged gashes, chopping up the rock into pinnacles and spires (Plates 1 B, 4 B).

Within the limits of our map the Kanab does not attain this grandeur of form. Only along the eastern base of the Pine Valley mountains is the entire formation exposed; and there it has an ancient subdued topography that has had little chance for reconstruction through a renewal of slopes, as will be shown later.

The Colob formation, also, in the vicinity of Toquerville, is not displayed to best advantage. Along the Pine Valley range it forms rounded foot-hills and long sloping ridges, which have little individuality, aside from their pure white or occasional buff color. Far to the eastward, at the Temples of the Virgin, and along the marvellous White cliffs, the more magnificent features of sculpture are brought out by active erosion (Plate 4 A). Even in our region, however, where recent erosion has been actively at work, the structural detail of the Colob is well shown, in long sweeping curves of cross-bedding. The slow crum-

bling away of the fine white sand grains brings out the frost-work pattern in a way that is at once pleasing and grotesque. The mysterious name Colob is well suited to it.

The Cretaceous and Tertiary formations are of little importance in the region in which we worked; for only on the eastern flank of the Pine Valley mountains did we see them exposed in entirety, and the remoteness of this part of the region from the Hurricane fault line, together with the evident simplicity of structure of the range turned our attention away from this part of the rock series. On Colob the light brownish Cretaceous sandstones, limestones, and shales occur, and coal beds are associated with them. A small patch of Cretaceous is exposed in the canyon of Ash creek not far below Toquerville, but in general the remnants of both the Cretaceous and the Tertiary on the downthrown western side of the fault are concealed beneath lavas. Of the Tertiary beds, which are mostly weak shales and limestones, one member, a coarse quartz-pebble conglomerate, is prominent here, in that it furnishes quantities of quartz cobbles and pebbles which make up a noticeable part of the recent gravels of the district.

Geographical Conditions under which the Strata were deposited.

The geographical history of the Plateau province during the long period from the Devonian era to the end of the Eocene has been well described by earlier observers, who state that it is characterized by deposition under slowly changing conditions which were uniform over a large area. The best account of the region is that of Dutton, of whose conclusions a brief summary will be given. After that a few points will be discussed where further study suggests that during Triassic and Jurassic times land conditions may have lasted longer than has been supposed.

Devonian and Carboniferous Deposition. During the Devonian era or perhaps earlier, at the end of the second long period of erosion of which evidence is found in the walls of the Grand canyon, the sea advanced upon an early Paleozoic or Archæan surface of small relief. After the Tonto sandstones and shales had been deposited upon this, the Lower Carboniferous or Red Wall strata of quartzitic sandstone were laid down in gradually deepening water which in time became deep enough for the deposition of the heavy Upper Red Wall limestone.

"The lower Aubrey group corresponding to the coal measures is a series of sandstones of exceedingly fine texture and often gypsiferous. There is a notable absence in these beds of signs of very shallow water. . . . On the other hand there is no reason to suppose that the depth was at all profound" (*c*, p. 210). "In the upper Aubrey series we come upon some indications of shallow water, and from the base of the Permian upwards these are ever present. In the Permian, Trias, and Jura we find instances of . . . peculiar unconformities by erosion without any unconformity of dip in the beds. Perhaps the most widely spread occurrence of this kind is the contact of the summit of the Permian with the Shinarump conglomerate, which forms the base of the Trias. Wherever this horizon is exposed this unconformity is generally manifest. Between the base of the Permian and the summit of the Carboniferous a similar relation has been observed in numerous localities, and there is a similar instance in the lower Trias. It has also been detected between the Trias and Jura, and between the Jura and Cretaceous" (*c*, p. 211). "During the entire [Mesozoic] age the surface of deposition was always very near the sea-level. The proof of this is abundant and clear. Throughout the Plateau province the strata are all shallow water deposits. Fossil forests, ripple-marked shales, frequent unconformities by erosion without discrepancy of dip, cross-bedded sandstones, occasional retirements of the waters, all mark very shallow water in the Permian, Trias, and Jura; while coal, carbonaceous shales, abundant remains of land plants indicate the same for the Cretaceous. And finally, the absence of all traces of appreciable displacement except along the coasts combines to prove that the Mesozoic beds were deposited with almost rigorous horizontality, and very nearly at sea-level, throughout the entire Mesozoic" (*c*, p. 69). "Now and then the waters retreated from [the surface of deposition], but only for very brief periods. On the whole deposition proceeded almost continuously" (*c*, p. 211).

"From six thousand to fifteen thousand feet of strata were deposited over an area of more than one hundred thousand square miles with comparatively few unconformities and contemporary disturbances, while the level of the uppermost stratum remained at sensibly the same geographical horizon. . . . The case is analogous to that of the Appalachians during Palæozoic time," and the conditions during the western Cretaceous are especially like those of the eastern Carboniferous. "The more we reflect upon the similarity the stronger does it become. It fails, however, when we come to reflect upon the phenomena presented in the two regions in the period subsequent to the deposition; the Appalachian

strata were flexed and plicated to an extreme degree, while those of the west are for the most part calm and even. Only in the vicinity of the mountains and shore lines do we find them much disturbed" (*a*, p. 13). All the Mesozoic beds are remarkably uniform in thickness, lithological character, and minute structure such as cross-bedding over the whole great plateau area from the Pine Valley mountains to Western Colorado, and from the middle of Arizona to the southern margin of the Uintas. They are thicker on the edges near the old shore line, and diminish quite rapidly for two or three leagues, but after that the diminution is very slow (*c*, pp. 47, 48, 208).

During the beginning of the Tertiary marine deposition continued in many places, but soon the region was elevated and vast lakes were formed. Sedimentation continued in these to an enormous extent, although gradually the lakes were filled or desiccated, those at the extreme south becoming dry first and those at the north near the Uinta mountains persisting longest (*a*, pp. 216–219).

The main outlines of this history, as thus summarized from Dutton's account, have been placed beyond a doubt by the painstaking work of the earlier observers. When they wrote their reports geologists were only beginning to understand that it is possible for thick and extensive deposits to be laid down on land without the intervention of large bodies of water. Accordingly they assumed that all the Paleozoic and Mesozoic strata of the Plateau province were marine, and the Tertiary strata lacustrine. Professor Davis (*a*, p. 373) has raised the question whether these may not be only in part lacustrine, while perhaps a larger part were deposited subaerially in the form of fluviatile fans, deltas, and flood plains. As Tertiary strata occur but scantily in the Toquerville region and are only of Eocene age, their history will not be further considered. Nor will Paleozoic history be considered, since we have no data beyond those which were available to Dutton. Although the cross-bedded sandstones in the lower part of the Aubrey remind us of the need for further study, there is no reason for doubting the main conclusion that most of the Devonian and Carboniferous strata were deposited in a sea of moderate depth. The Moencopie series was probably laid down in a shallow sea where estuarine conditions may possibly have prevailed, as is indicated by the intercalated layers of gypsum, and the almost total lack of fossils in strata admirably adapted to their preservation had they existed.

THE SHINARUMP LAND. At the close of the Permian, or Moencopie, the sea retired (Dutton, *c*, p. 211) and the greater part of the Plateau

province was exposed as a plain with a slope so slight that but very little erosion took place. Plants covered this plain, at least in those parts where we saw the unconformity, as is shown by the layer of carbonaceous matter lying just below the surface of that time. The Shinarump conglomerate lying just above has been supposed to indicate an immediate return of the sea. There is another possibility, however; and we should like to raise the question whether this may not be a continental deposit which was gradually built outward from the former shore line of the Moencopie sea. It seems as though when, at the beginning of the Shinarump period, the former sea bottom was so far elevated as to become a low coastal plain, the land must still have continued to pour upon it countless streams of waste which would have spread out in the form of very gently sloping confluent fans. If such deposits were formed they would be comparable to those now forming in the low plains of northern India (Blanford, pp. 382–389) and the high plains at the eastern base of the Rocky mountains (Johnson, pp. 613–622). The very fact that the Shinarump is more or less conglomeratic in all parts suggests a subaerial origin. In the ocean it is hardly probable that pebbles even though small should be carried a hundred miles directly out from the shore and scattered evenly over a hundred thousand square miles of the sea bottom. Yet such must have been the case if the Shinarump is a marine deposit. If, on the other hand, it is a subaerial deposit the pebbles are just the sort of small bits of quartz that would gradually be washed farther and farther out over the plains by streams descending out of the mountains. A still stronger suggestion of land conditions is found in the arrangement of the sand and gravel of the formation. In Toquer Hill, for example, we have a coarse sandstone with streaks of quartz conglomerate, sometimes forming long regular bands of pebbles ranging up to an inch in diameter, at others composed of little flinty pebbles scattered through the sandstone at long intervals. Still again it forms old stream channels with distinct lateral unconformities, or caps the truncated edges of a series of cross-bedded sandstone layers. Cross-bedding on a rather large scale is common. Near the top of the Shinarump petrified wood is abundant, and we found one complete trunk sixty feet long. The lateral unconformities and cross-bedded strata capped by horizontal conglomerate beds are difficult to explain except as a result of stream action. The petrified wood has been supposed to have been floated into the sea from distant shores and to have become water-logged and to have sunk in all parts of the plateau province. If this is the case it is difficult to see why the wood

is confined so strictly to this particular horizon at the top of the Shinarump. The land must have been forested both before and after the time represented by this formation, and there must have been winds and currents to carry the tree trunks. If the Shinarump is a continental deposit, the difficulty disappears. On the first emergence of the land above sea-level vegetation would be lacking. Therefore the lower Shinarump would contain no fossil wood. Later the whole country would become forested and many trees would be buried under fluviatile deposits. Lastly, when the sea again encroached upon the land the whole forest would be buried in the new marine sediments, and we should find, as is the case at Toquerville, that this particular layer would be especially rich in fossil wood.

One hundred and fifty miles southwest of the region that we have been discussing, Ward in his study of the district around the Little Colorado river has found similar and even more marked indications of land conditions. The Shinarump formation there increases to a thickness of sixteen hundred feet, and is characterized throughout by fossil wood and other signs of terrestrial origin (p. 405). The conglomerate "contains somewhat large, but always well-worn pebbles and cobbles derived from underlying formations; still it rarely happens that this aspect of the beds forms the major part of them. In the first place the conglomerate tends to shade off into coarse gravels and then into true sandstones. These . . . are always more or less cross-bedded and usually exhibit lines of pebbles running through them in various directions. . . . Although the sandstones proper generally occur lower down, still there is no uniformity in the arrangement, and sandstones are often found in the middle and conglomerates more rarely at the top." In addition to these the Shinarump (p. 406) embraces other classes of beds, chiefly well-stratified thinnish sandstone shales which often thicken in short distances and become transformed into bluish-white marl. In the lower valley of the Little Colorado, where the Shinarump conglomerate is only three hundred feet thick, this feature is not prominent, but elsewhere, as in the Petrified Forest region where the formation attains a thickness of seven or eight hundred feet, "this tendency on the part of certain beds to become transformed into marls is the most marked feature of the formation. . . . These heavy marl beds . . . are interstratified between conglomerates, coarse gravels, and cross-bedded sandstones. . . . These varying beds . . . often change the one into the other even at the same horizon within short distances" (p. 406).

Overlying the conglomerate proper are the Le Roux or Belodont beds

of variegated shales in which Ward (p. 407) has found numerous remains of terrestrial vertebrates. These too "are found stratified between the sandstones by the transformation of certain shales into marls. If these beds are carefully traced a short distance in the direction of the dip, they will be seen to thicken very rapidly and soon to take on the character of true variegated marls" (p. 409). They start beneath a bed of sandstone which thins out to nothing when followed horizontally, while at the same time the marl beds thicken greatly and overlap upon beds of conglomerate. In brief the Shinarump here consists of beds of very varying coarseness which merge into one another, thicken rapidly, or die out with the greatest irregularity. In addition to this many layers consist of cross-bedded sandstone, others are marly, and still others contain irregular trains or layers of pebbles. Lastly, the whole formation is full of petrified wood, and part contains the fossil remains of land animals. All these conditions are unlike those of ordinary marine deposition, but are exactly what we should expect in continental deposits laid down by streams or in occasional lakes.

The thin Shinarump deposits near Toquerville and the thick formation which occupies a corresponding position near the Little Colorado river both show a rapid thinning of the strata toward the great central plateau region. This is what would naturally be expected if the deposits were subaerial. In the central region, however, to judge from the reports of Dutton and others, the Shinarump seems to have a uniform thickness over a large area. Such uniformity is characteristic of marine deposits, and it may be that part of the Shinarump is marine. It is possible, however, that part of the formation was laid down by a retreating or oscillating sea, or that the strata were laid down in a shallow basin the centre of which was so far from the source of supply that the streams could not bring to it more than a few feet of sediment, which they distributed with considerable uniformity. As yet we have not sufficient evidence to justify us in saying that the Shinarump as a whole is either marine or non-marine. It is an open question, but the weight of evidence seems to indicate that in part at least it is non-marine.

THE PAINTED DESERT PERIOD. Although the Painted Desert strata which succeed those of this doubtful land period contain no fossils, they are supposed to be the result of marine deposition. They are evenly stratified and continue unchanged for long distances. They consist of soft sandstones, thin in our area, but nine hundred feet thick along the Little Colorado river.

THE KANAB PERIOD. In the regions far from the coast uniform conditions may have prevailed unbroken to the end of the Mesozoic. Near the shore, however, there was a break at the beginning of the Kanab period, as is shown near Toquerville by a bench-making layer of mauve sandstone one hundred feet thick in which the strata are strongly cross-bedded on a large scale. Throughout the overlying massive red sandstone there is an alternation of cross-bedded and horizontal strata, suggesting that during the long period of their formation there was a constant change of conditions. Although conditions of uneven deposition, like those which will be discussed in connection with the succeeding Colob formation, prevailed to a great extent and caused the cross-bedding, there seem to have been shorter times of even deposition like that of the Painted Desert period.

THE COLOB PERIOD. The Colob period, which follows the indeterminate Kanab, seems to be unique in geological history. Its strata, like those of the Shinarump, have been tacitly assumed to be of marine origin, and there has been little or no attempt to account for their peculiar features. A study of these leads us to query whether this too may not be of continental origin. The Shinarump suggests a piedmont deposit formed during a time when many streams flowed out upon a coastal plain, and when the climate was moist enough to allow the growth of forests upon the lowlands. The Colob suggests a piedmont deposit formed during a time when the climate had become so dry that a great desert drifted its sands in huge dunes over an area as large as the state of Indiana.

In the lofty plateau east and northeast of Toquerville the strata are but slightly tilted, and fine vertical sections are exposed in the steep walls of numerous narrow canyons. The best example of these that we saw is Kanab canyon, although the same features are almost as well displayed in several other places. Here the white sandstone is cross-bedded on a scale so large that a single layer attains a thickness of from five to fifty feet. Most of these layers have a very persistent and uniform dip of twenty or twenty-five degrees varying in direction from southeast to southwest. Other directions of dip are seen, but they seem to be rarer and less steep. The top of every inclined bed is smoothly truncated by what at first seems to be a horizontal layer, from which rises a new cross-bedded series. It is remarkable, however, that in every case where the strata were closely examined this apparently horizontal layer proved to consist of the lower portions of the overlying inclined strata, which, as they approach the underlying plane of trunca-

tion, assume a curve tangent to it, and finally die out as they become horizontal. Everywhere the deposit consists of uniformly fine white sand without a trace of pebbles or of coarser sand so far as has yet been observed. The uniformity of texture is emphasized by the total lack of ripple marks, which, as Cornish (*a*, p. 280) has shown, result from the mixture of sand grains of different sizes. That such a formation could be due to marine or lacustrine action of any kind seems contrary to what we know of such agencies. It is generally recognized that cross-bedding of a marked type is a proof that the deposits were formed close to the shore or on land. The uniform thickness of the Colob sandstone over so great an extent renders it antecedently improbable that it is a shore deposit; the total absence of ripple marks, rill marks, and other characteristic shore features lends support to this, and lastly the perfect smoothness and horizontality of the planes which truncate the tops of the strata render this still more improbable. At the time of the formation of a given cross-bedded layer which is now fifty feet thick and has a dip of twenty-five degrees, the water would have had to be over fifty feet deep, since in their untruncated condition the strata must have had a greater thickness than at present. The question then becomes: Is it possible that in a body of water sixty or more feet deep the waves or tides or currents should first carry away five or ten feet of sand, and then without disturbing the perfectly smooth surface thus formed lay down on it other layers of sand having a dip of twenty degrees and rising fifty or sixty feet above the base on which they were deposited? And could this process go on uninterruptedly over an area of thousands of square miles? We cannot affirm that it is impossible, but we can affirm that it is improbable, and nothing of the kind seems to have been observed in actual formation. The same facts of structure, together with the total absence of gravel, of fossil stream beds, and of lateral uncomformities render it equally improbable that the Colob was deposited by fluviatile processes. The only remaining possible agent is the wind. We cannot yet be certain that the Colob sandstone is a wind formation; nevertheless none of its characteristics seem to oppose such an hypothesis. The uniformity and fineness of the component quartz grains, the steepness of the cross-bedding, its general uniformity with interesting minor variations, the even truncation of the successive cross-bedded strata, and the tangency of the overlying layers to the plane surface thus formed suggest a series of great white dunes marching forward to the east and south from the base of the Basin Range mountains. Far to the southeast the Colob sandstone grows thinner (Ward,

p. 412), and in New Mexico dies out or is merged in the underlying Kanab formation (Dutton, c, p. 37, a, p. 152). Much further observation is needed before we can arrive at a settled conclusion, but meanwhile it seems to be a fair question whether the cross-bedded strata of the Kanab and Colob formations may not be continental deposits laid down by the wind.

At the end of the Colob period the encroaching Cretaceous sea buried the desert, if desert it really was, and preserved a series of strata which to-day present some of the most magnificent scenery in the world. The upper Kanab canyon with its weird tracery, where the wind has brought into strong relief every line of the criss-cross laminæ; the Temples of the Virgin, where great snow-white domes, turrets, and buttresses rise thousands of feet above the valleys; the gleaming rounded masses of the Colob plateau, standing in sharp contrast to the immense red precipices below them and the green wooded plateau and blue sky above, — all these and many other wonderful scenes we owe perhaps to a great dreary desert of long ago.

Summary. In reviewing the physical history of the Plateau province from the Devonian to the end of the Eocene, as revealed in the strata of the Toquerville region, it appears that on the whole it was a time of slow and steady depression during which deposition was almost uninterrupted. The surface of deposition stood close to sea-level all the time. There were two chief periods of quiet marine deposition, separated by a period of very uneven deposition. This latter was divided into two parts separated by a relatively brief interval of quiet deposition. The first period of uneven deposition was characterized by great variation in the texture of the materials deposited and in the manner of their deposition, and by the preservation of terrestrial fossils. The second was characterized by remarkable uniformity in the texture of the materials and in the manner of their deposition. Arranged in tabular form, the chief periods are as follows: —

1. The long interval between the Devonian and the end of the Moencopie was distinctly a marine era of even deposition, although the lower beds of the upper Aubrey are somewhat uneven.

2. The period of uneven deposition lasts from the beginning of the Shinarump to the end of the Colob. It may be subdivided into three parts: —

A. The Shinarump proper and the lower half of the Le Roux were a time of great diversity in deposition. Coarse gravels and marls were deposited side by side; lateral unconformities, fossil stream beds, and

frequent cross-bedding indicate that the water in which the strata were deposited was moving rapidly in flowing streams or shallow lakes; fossil trees and the bones of terrestrial animals show that land cannot have been far away. Many things suggest that this was a period when the country was elevated above the sea and supported abundant life, both animal and vegetable.

B. During the upper half of the Le Roux there was a return to conditions of even, probably marine, deposition, which continued to prevail during the following Painted Desert period.

C. The next periods, the Kanab and Colob, are unique because of the great unevenness with which the strata are bedded and the remarkable uniformity of the sand which composes them. This seems to have been a time when no life flourished. Possibly the deposits are terrestrial and are the product of wind action in a great desert.

3. At the end of the Jurassic and beginning of the Cretaceous a marine phase of even deposition again prevailed for the last time, but after the Cretaceous was fairly under way it passed into the alternating estuarine and swampy conditions under which the coal measures were deposited.

4. Lastly, came the Tertiary with its conditions of uneven terrestrial deposition, which have continued down to the present.

In regard to climate the formations, so far as land indications are concerned, suggest that from Carboniferous onward there was an increase in aridity culminating in the arid conditions which produced the Colob desert. Then the climate grew more moist and equable, so that many plants and animals flourished during the Cretaceous and Tertiary periods. Changes of all kinds took place slowly and on a large scale.

The First Uplift.

The various writers on the Plateau province agree that the long period of quiet deposition extending from Devonian to Eocene times gave place at the end of the latter to an era of exactly the opposite character, marked by great earth movements, extensive vulcanism, and prolonged erosion. The phenomena of the Toquerville district agree perfectly with this, and add some details which have not before been placed on record.

VULCANISM. At the end of the Eocene or early in the Miocene, when as yet erosion had made no noticeable impression upon the strata of our area, and perhaps even while they were still under water, volcanic eruptions began to occur. In the very southwest corner of Utah a great

mass of andesite and trachyte was poured out, the remains of which now form the Pine Valley mountains and some small hills northwest of Toquerville. The Pine Valley lava lies upon the youngest Eocene strata in a gentle syncline, which may have been formed either before or after the extrusion of the lava, or may be due in part to the bending of the strata under the weight of the extruded mass. The smaller andesitic hills near Toquerville are either intrusive portions which never reached the surface, or stocks of extrusions of which all other traces have now been removed. This lava seems to be of nearly the same age as the oldest of the successive flows that took place in the region of the High Plateaus farther northeast (Dutton, *a*, pp. 59, 180). Its relation to the flexing and folding to be described in the following paragraphs is uncertain. The fact that the lava covers a surface where little or no trace of erosion has been observed makes it seem probable that the volcanic material was extruded before the flexures and folds were completed. The latter are of great size, and, if accepted theories are correct, required a long period for their completion. Moreover, the flexures are of such a nature that the Toquerville region must have been elevated some thousands of feet above sea-level. At the close of the period of folding, therefore, the sedimentary strata underlying and surrounding the Pine Valley mountains must have been exposed to erosion for a considerable length of time, unless they were in some way protected. If the lava was not extruded till after the completion of the folding, the surface of the Eocene strata ought to show considerable erosion. Wherever the contact of the Eocene and volcanic formations was observed there was no evidence of such erosion. The observed localities, however, were so few, and the contact was so often covered with talus, that no positive conclusion can be drawn. We may provisionally conclude, then, that this oldest lava of our region was extruded before or during the period of flexing and folding which we shall now discuss.

Flexing and Folding. This folding is a feature peculiar to the area immediately around Toquerville. East of a line drawn along the southern portion of the Hurricane fault and extended northward up the valley of Le Verkin creek, the strata are nearly horizontal. Between that line and the old shore line of the Mesozoic sea west of the Pine Valley mountains the strata are compressed into two synclines and two anticlines which culminate in a great overturned fold at Kanarra. North of Kanarra the continuation of these plications was not studied; toward the south they gradually die out until, fifteen or twenty miles beyond Toquerville, they have greatly broadened and persist only as gentle monoclines dip-

ping toward the east. The most western of these folds is the broad gentle syncline in which lies the lava of the Pine Valley mountains. In the neighborhood of the mountains the dip is everywhere gentle, and the flat bottom of the trough is several miles wide. Toward the southwest this syncline almost vanishes, but the western limb seems to persist as an eastward dipping monocline whose lower limit is now the Grand Wash fault (Marvine, p. 196).

The next fold to the east is a remarkable anticline which runs northeast eighteen miles from Price City south of St. George to Leeds, where it bends more to the north for ten miles, until it is lost under alluvium and lava a short distance north of Bellevue. When what seems to be the same fold reappears at Kanarra it has again bent somewhat to the northeast. Although near St. George this fold is finely exposed as a typical breached anticline, that portion fades into insignificance when compared with the extraordinarily diagrammatic portion near Harrisburg and Leeds. Here erosion has removed all the strata as far as the Shinarump, which at Leeds forms a great rounded nose pitching toward the north and shaped like the decked front of a round-topped canoe (Plate 2 B). As the anticline rises toward the south, the deck of the nose gains a greater elevation, until, halfway from Leeds to Harrisburg, the centre is broken open where it has been undermined by the wearing away of the soft Moencopie shales. A few miles farther south a five minutes' walk from the road southwest of Harrisburg brings one to the top of the Shinarump cliffs on the northwest side of the anticline. Under the observer's feet is the hard Shinarump formation dipping to the northwest at an angle of forty degrees. On its resistant surface erosion proceeds very slowly, and for many miles this edge of the anticline forms a ridge. In front of the observer a precipitous cliff fifty or sixty feet high bounds abruptly a perfect anticlinal trough, a mile or more wide, a sort of hand specimen or model showing at a glance a diagrammatic type not only of an anticlinal trough, but also of an anticlinal ridge. Under the Shinarump cliffs lie the bright-colored Moencopie shales, red, gray, and brown, the edges of which are truncated like those of the overlying sandstone and conglomerate although at a lesser angle. At the very centre lies a little rounded ridge where erosion has laid bare the harder underlying Aubrey limestone, which rises as an anticlinal core in the midst of an anticlinal trough. Beyond the ridge the naked parti-colored shales again rise gradually in brilliant bands to a Shinarump cliff exactly like that on which we are standing, except that it faces in the opposite direction and dips to the southeast.

North of Bellevue where the fold disappears under a covering of lava it is still a normal anticline, but where what seems to be the same fold reappears at Kanarra it has been compressed to such an extent that it has been completely overturned and the strata lie in inverted order with a rather steep dip to the northwest. As this fold has been cut at this point by both the old and the new Hurricane faults, only a small portion is now exposed.

The trough lying east of this anticline is unimportant. It dies out completely south of Toquerville, while at Kanarra it is so far compressed that the two limbs touch each other. The most eastern anticline lies close to the line of the Hurricane fault. On the south it flattens out, although the eastern limb persists as an eastward dipping monocline at the base of which is the Hurricane fault (Dutton, c, p. 114). In the northern half of the region covered by our map it is a strong arch with a dip of from twenty to forty degrees. The ridge east of Bellevue is formed where it brings up a hard core of Aubrey limestone which has since been bisected longitudinally by the Hurricane fault. On the eastern side of this core all the overlying strata have been stripped off; on the western side where the country has been dropped far down by the fault, the overlying strata are to a great extent preserved.

In a preceding section certain passages from Dutton were quoted, in which he calls attention to the marked resemblance between the conditions of deposition in the Appalachian province of the east during Paleozoic times, and those in the Plateau province of the west during the Mesozoic. Especial attention was called to the close similarity of the eastern Carboniferous which immediately preceded the chief Appalachian folding, and the western Cretaceous which preceded the period of folding that we have been discussing. The similarity seems to be even greater than has been supposed, for in both places at the end of the period of deposition the border region close to the shore of the denuded old land was notably, though doubtless very slowly, elevated. Close to the shore, just where the deposits of the preceding ages had accumulated to the greatest thickness, the uplift was greatest. Here too flexing and folding were induced in lines parallel to the former sea margin, while the strata that lay farther out to sea were almost undisturbed, and now lie essentially horizontal, both in the Allegheny plateau on the one hand and in the plateaus of the Colorado on the other. It seems to be a well-established conclusion that in the Appalachians this folding was due to pressure exerted in a direction tangent to the earth's crust and at right angles to the shore line. This acted in such a way that the upper

parts of anticlinal folds appear to be shoved away from the old land, and the plications now stand in unsymmetrical attitudes. In the Plateau province most of the flexing is monoclinal and of far simpler character than in the Appalachians. As these displacements involve but little horizontal compression, it has generally been assumed that they are due to the action of vertical forces by which one block was merely raised above or depressed below another (Gilbert, *b*, p. 86). In the Toquerville area and northward, however, we have a small district which has evidently been subjected to tangential pressure. The folds thus produced are of the true Appalachian type, and at Kanarra are thrust over one another on a small scale, just as is the case in certain parts of the eastern mountains. Both in the East and in the West the direction of movement was such as to incline the tops of the anticlines away from the neighboring old land. South of the Pine Valley mountains these true folds of the Plateau province flatten out into monoclinal flexures. The query arises whether the monoclinal flexing of the Plateau province as a whole may not be a phase of a close folding of the Appalachian type, where for some reason most of the strata were affected but slightly. The manner in which the folds of the Toquerville region are intensified immediately east of the great lava mass of the Pine Valley mountains and bend around parallel to it is certainly remarkable. The mind at once attempts to formulate some causal relation, but that would be going farther than is warranted by our present knowledge.

Gilbert (*a*, p. 62) has suggested that the faults of the Basin Range and Plateau provinces are the superficial expression of a deep-seated structure such as that of the Appalachians. Otherwise expressed, his hypothesis is that far below the surface there was great tangential pressure which forced the lower part of the crust into plications of the Appalachian type. The superficial layers, however, were not so folded, but were raised and broken into blocks, as a sheet of ice may be broken by a wave that passes under it. This hypothesis seems to agree with all the known facts, including the new ones found in the Toquerville region. In Gilbert's discussion he has shown (*a*, p. 59), as has also King (*a*, p. 744), that the Tertiary faults of the Basin Range and Plateau provinces follow the same lines as the plications of an earlier Jurassic upheaval. He has not, however, distinguished between the folding and flexing which took place in the early Tertiary on the one hand, and the periods of faulting which we shall later show to have occurred at the middle and end of that era. If Gilbert's hypothesis is correct, the strata that were deeply buried at the time when the earth's crust was dis-

turbed must have been highly folded, those at moderate depths must have been gently flexed, and those near the surface must have been faulted. None of the deep-seated strata are to-day exposed. The strata in which the Jurassic and early Tertiary plications are now visible at the surface were at the time of folding buried beneath a moderate depth of overlying strata, and usually show gentle folds formed without faulting. Those layers in which the later movements are shown were relatively close to the surface, and are almost always faulted without bending, since they were free to break as soon as they were strained. The line of greatest displacement seems to have shifted eastward from the Basin Range province in Jurassic times to the western margin of the Plateau Province in the early Tertiary, and to the centre of this latter province in the middle Tertiary. In the most recent uplift it has shifted back toward the borderland between the two provinces.

Resulting Topography. At the end of the period of folding and flexing, which was probably completed early in the Miocene, there must have been a time of quiet of uncertain duration, the turning-point between the movements which we have been discussing and those of an opposite character which followed. Let us pause long enough to get in mind the condition of the country at this time in so far as we are able to restore them. As we have seen, the region around Toquerville had been thrown into a series of close folds which toward the south fade into eastward dipping monoclines. Farther east there were a number of similar monoclines (Dutton, c, pp. 41, 115, 128, 185). On the basis of these facts we can to a certain extent reconstruct the topography of the country, although erosion, the amount of which we cannot measure, must have greatly changed it from the simple forms due merely to the original rock structure. To the west lay the elevated and probably maturely dissected "old land" which is now the Basin Range province. East of this was an extensive area of recently uplifted sediments, a raised and more or less folded and flexed coastal plain. Neglecting for the moment the effects of erosion, the western part of this consisted of a narrow belt of closely folded mountains near Toquerville not far from the old sea margin. The greater part of the coastal plain, however, consisted of a series of broad initial terraces which descended gradually eastward toward the distant sea, and of which the steep portions were formed by the gently dipping monoclines. To what extent the strata had been dissected and removed by erosion we cannot say, nor do we know the course of the streams. If the drainage was consequent, as would in all

probability be the case on such an uplifted coastal plain, the main rivers ran eastward, in a direction opposite to that which they now follow.

The First Faulting.

We may now consider the first faulting, whereby these monoclines, which ran north and south, were cut longitudinally by great faults. The plateau region now became a series of blocks, separated by faults, which in each case involved an uplift on the east and a downthrow on the west. Dutton (*c*, pp. 21, 41, 113), Gilbert (*a*, p. 54), and Marvin (p. 196), all speak of the fact that all the great faults of the plateau region, which at present determine the leading features of the topography, follow the lines of older monoclinal flexures that dip east. "It is certainly remarkable that the distinct flexures of the Grand Canyon district dip eastward so generally, while the faults have their throw to the west with almost equal regularity. In all cases where this obtains, the later movement by faulting was of greater measure than the earlier movement by flexing. It is further noteworthy that the unfaulted or least faulted flexures . . . lie to the east, while the distinctly faulted flexures lie to the west" (Davis, *b*, p. 149).

The fact that the displacement by faulting is exactly opposite in its vertical effect to the earlier movement by flexing seems to indicate that the two movements represent two distinct periods of uplift, — an earlier one which, in the Toquerville district at least, witnessed tangential pressure of the Appalachian sort, and a later one in which there was only vertical uplift.

The fault with which we are chiefly concerned — the old Hurricane fault — may be traced from the Colorado river northward one hundred miles to Kanarra. It probably extends far beyond these limits; but that is a matter for future study. At Coal spring, twenty miles north of the Colorado river, we first saw the old fault; next we visited it at a point on the Hurricane, fifteen miles north of Coal spring; and again, after an interval of twenty-five miles, near Antelope wash. From near Fort Pierce, about on the Utah boundary, we followed it to Kanarra, making this portion of the fault line our special study. Along this part, the Utah part, of the Hurricane, the evidence of the old fault is associated in rather a confusing way with the more apparent evidence of the second faulting, which is much more recent, and gave rise to the present Hurricane scarp. South of the Arizona line, however, the Hurricane fault,

so far as we have observed it in the field, consists chiefly of the old fault, with the newer displacement greatly diminished.

Near Coal spring, for instance, we found no signs of a recent fault; but beneath a protecting basalt cap that forms a promontory in the Hurricane ledge there was displayed a portion of the old fault line. The lava rests on a nearly level surface that horizontally truncates the old fault. Beneath the black cap the red Moencopie shales on the downthrown western side of the fault butt against the gray Aubrey limestone on the east of it.

The amount of dislocation shown by this relation of strata is about six hundred feet, and is much less than the throw of the old Hurricane fault

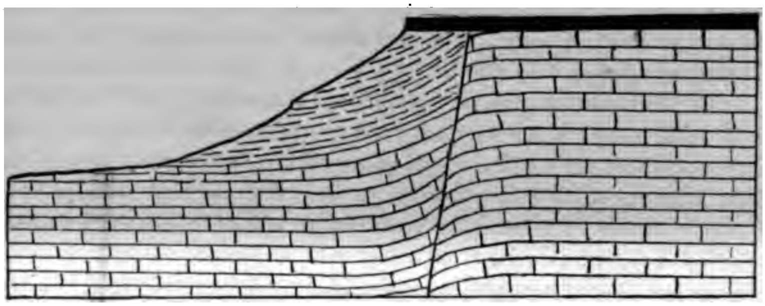


FIGURE 4.
The Hurricane fault at Coal spring.

farther north. That this is not a recent fault is demonstrated by the surface on which the lava lies. This, as will be seen later, furnishes evidence of a long period of erosion that reduced this part of the country nearly to base-level before the more recent faulting took place.

Hardly less apparent than the Coal spring exposure, and certainly more striking because of its greater complexity, is the fine cross-section on the Hurricane just southwest of Gould's ranch. Here a section about a mile long contains a record of the ancient faulting, the succeeding long period of erosion, the basalt flows, the second or modern faulting, and recent erosion (see Plate 7, section G–H). The observer, from one of the little lava mesas that overlook the Hurricane ledge, sees directly at his feet the red and gray Moencopie shales sloping steeply down to the top of the cliff proper, which consists of hard Aubrey limestone, and drops down abruptly one thousand feet. At the base of the Aubrey cliff, or fourteen

hundred feet below the observer, lies black lava that matches the basalt cap on which he stands. He recognizes that in this discordance of altitude of the two parts of the lava sheet he has a measure of the recent fault, which formed the steep scarp. But his eye discovers more than this. Down beneath the lava that lies beyond the cliff he sees the brick-red Kanab sandstone. We can quickly reconstruct the section before him, as it must have looked just after the lava flow and just before the recent faulting, by imagining the ground on which he stands to sink fourteen hundred feet until the lava cap of the mesa lies alongside the lava west of the fault line. On the east, under the lava, there is lower Moencopie shale; on the west, under the lava, is Kanab sandstone. The flow of basalt covered an ancient fault. The lava must have flowed across a base levelled fault line where a displacement of about fifteen hundred feet had brought Kanab against Moencopie. The lava itself was then faulted, forming the present scarp.

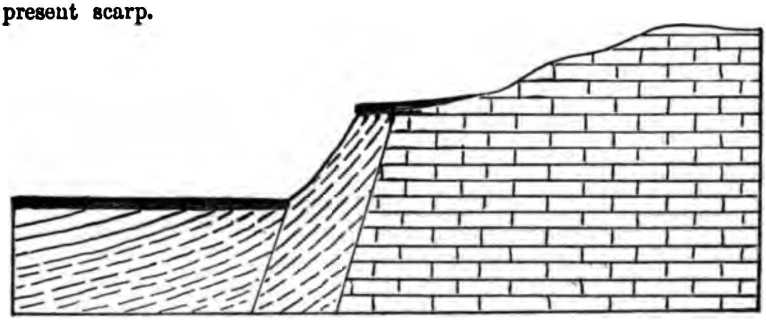


FIGURE 5.
The Hurricane fault at Virgin canyon.

Near where the canyon of the Virgin river cuts through the Hurricane ledge, there is a condition of things somewhat similar to that just described (Fig. 5). The steeper part of the escarpment, as before, is the product of the recent fault, which has here a throw of only three hundred feet. Up the canyon, just east of the scarp, a part, at least, of the old fault is shown by an exposure in the canyon wall. Here again the old fault is preserved under a basalt sheet. On the lifted eastern side of the fault, Aubrey limestone lies nearly horizontal; against it on the downthrown side are Moencopie shales that dip steeply towards the west (Plate 3 B). On either side of the river, where it crosses the old fault line, warm sulphur springs issue from the foot of the canyon walls. Within half a mile of the fault, on its downthrown western side, a white

sandstone, probably Colob, that appears under the lava sheet, shows a very steep dip towards the west, although a little farther west in a second exposure this has greatly decreased. This sudden change of dip suggests that under the lava between the two exposures there may be another old fault in addition to the one seen at the sulphur springs. Of this, however, there is no proof; and the steepness of the dip alone may be sufficient to bring the Colob sandstone to its present low level on the downthrown side. The displacement as measured along the fault in the canyon is relatively small, bringing Aubrey against Moencopie. The entire displacement, however, including that due to flexing, amounts to thirty-five hundred feet, the vertical measure of the strata between the Aubrey and Colob formations.

From Virgin canyon northward as far as Toquer hill, the old fault seems to follow the Hurricane escarpment; for just south of Toquer hill, a few hundred yards west of the Aubrey wall, there are several exposures of red Kanab and white Colob sandstone that dip steeply west and are in places capped by gravel and lava. They are like the exposures of downthrown strata in the Virgin canyon, and seem to occupy a corresponding position on the same side of the old fault.

From Toquer hill northward to Kanarra, the old fault is covered, for a distance of twenty-five miles, under a belt of basalt and alluvium that stretches along the base of Bellevue ridge and of the escarpment of the Colob plateau. That the fault is merely concealed and does not die out is indicated by the fact that the displacement between the strata west of the lava belt and those of Bellevue ridge east of it is much more than that of the lava which is displaced by the new fault. Moreover at Kanarra an old fault is clearly distinguishable in the strata at the base of the Colob plateau. It crosses the prominent escarpment of the new fault at a very slight angle. To the northeast it cuts the overturned strata of the closest of the folds that have been described above, and seems to have displaced them many thousands of feet. At the line of the new fault it is cut off sharply as if by a knife. It seems highly probable that from Toquerville to Kanarra the old fault increases rather than decreases.

The Inter-Fault Cycle of Erosion.

After the completion of the first faulting the Plateau province entered upon a long cycle of quiet erosion which was brought to an end by a second period of faulting. During this inter-fault cycle the work of

erosion begun while the first faulting was in progress was carried forward to such an extent that the topography assumed a thoroughly mature character or even reached old age. The original topography due to faulting and folding was so far effaced that the valleys of the main streams were reduced nearly to base-level, forming the Mohavé peneplain. In the more remote regions there were low rounded mountains with well-graded slopes, and the Pine Valley mountains had almost as great relief as at present. Differences in hardness of strata produced practically no effect in the most completely base-levelled regions. Even in less eroded places erosion had gone so far that a fault scarp several thousand feet high had been worn away and even reversed, so that the hard strata of the downthrown side stood higher than the softer ones of the uplifted side. Near the end of the period there was considerable aggradation in many valleys, and numerous volcanoes poured out large sheets of basaltic lava.

The evidence of this long inter-fault cycle is found in facts of five classes which will be more fully discussed in the succeeding paragraphs. (1) The much greater northward recession of transverse cliffs on the upheaved than on the downthrown side of the faults demands a long lapse of time since the first faulting. (2) Many maturely dissected or even base-levelled surfaces belonging to the ancient topography have been buried by lava flows, and are now exposed in cross-section in the walls of young canyons or in the scarps of recent faults. (3) Portions of the lofty plateaus lying at a distance from their borders exhibit an upland surface of subdued graded slopes and broad valleys utterly different from the precipitous youthful slopes of the peripheral regions. This surface seems to be a part of the mature topography of the previous, or inter-fault cycle that has not yet been effected by the renewed erosion of the present post-fault, or canyon cycle. (4) At Kanarra the old Hurricane fault is crossed by the new one running almost parallel to it. The contrast between the mature topography of the one and the young topography of the other indicates a great difference in age. (5) During the latter part of the inter-fault cycle many valleys where erosion is now active were areas of deposition. The surface on which these deposits lie shows broad flat valleys the floors of which truncate highly inclined strata without reference to their attitude or texture. Corresponding to the valley floors are gently sloping grade plains, the sides of the ancient valleys, which lie at a higher level and are now being undercut. These two types of surface seem to indicate a previous topography far more mature than the present.

(1) Recession of Cliffs. In their present position the strata of the central and western part of the Plateau province have a gentle but very persistent dip to the north. It is often locally complicated by dips to the east due to faulting or by the eastward dip of the old monoclines. Its persistence and general uniformity of direction, however, find expression in the long lines of south-facing cliffs which cross the country at right angles to the dip. These are due to the alternation of hard and soft strata. As the later are continually worn away, the harder beds that overlie them are left without support and fall as talus, causing the cliffs to retreat continually northward down the dip. The hard talus that falls from the cliffs gradually piles up at their base and checks their rate of retreat. The amount of this checking depends on the rapidity with which material is carried away from the foot of the cliffs, and this in turn depends on elevation above base-level. Hence, where faults cut the cliffs at right angles, as the north and south faults cut the cliffs in the Plateau province, the cliffs on the heaved side, being at a greater elevation, are more fully exposed to the effects of erosion and retreat faster than those on the low-lying downthrown side. Powell (*b*, p. 191), Gilbert (*a*, p. 51), and Dutton (*c*, p. 200) all recognise this, but, as Davis has pointed out (*b*, p. 144), "they do not explicitly connect the amount of recession with the date of faulting." Moreover, as the same writer has shown, the present interval between the corresponding cliffs on the two sides of a fault represents not merely the amount of recession since the faulting occurred, but the excess of the retreat on the heaved side over that on the thrown side.

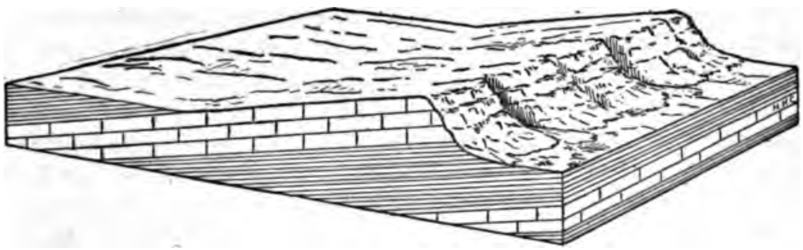
Near Toquerville the cliffs formed by the Kanab sandstone are fifteen miles farther north on the eastern or uplifted side of the Hurricane fault than on the western side. The first faulting must have taken place so long ago that the upper cliffs have had time to retreat fifteen miles farther than their counterparts on the thrown block. On the other hand, formations which are separated only by the later faulting match very closely on the two sides of the line of displacement, indicating that this took place quite recently. Between the two periods of faulting there must have intervened a long inter-fault cycle of erosion.

(2) Old Surfaces covered by Lava. Further evidence of the length of this inter-fault cycle is found in the old surfaces, portions of the ancient topography, preserved under recent lava flows, and now exposed in cross-section where the lava is cut by canyons or by the recent fault. Several of these have been already mentioned. It will be recalled that at Coal spring and at the mouth of the Virgin canyon lava

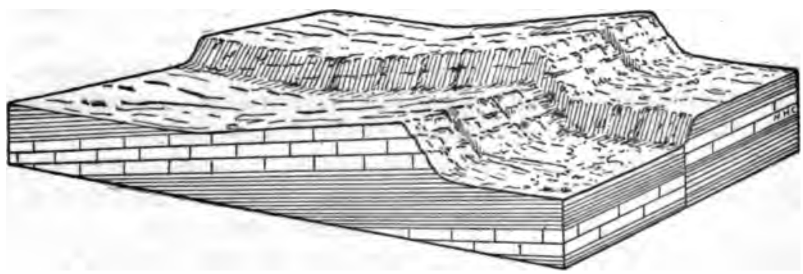
FIGURE 6.

BLOCK DIAGRAMS ILLUSTRATING THE DIFFERENTIAL RECESSION OF CLIFFS ON THE TWO SIDES OF A FAULT.

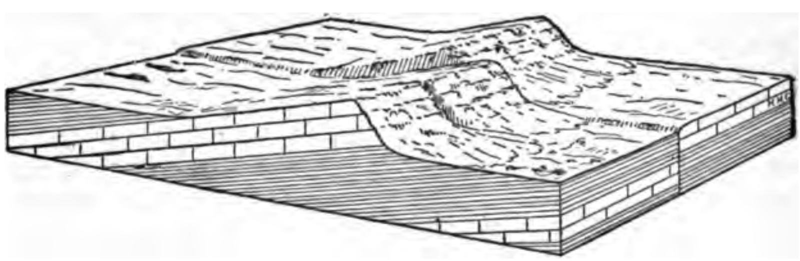
(From Journal of Geology.)



Unfaulted block showing a continuous line of cliffs.



The same block cut by a north-south fault.



The same block after erosion has almost obliterated the fault scarp. The cliffs on the eastern or upthrown side of the fault have retreated much farther than those on the downthrown side.

flows across the old fault, on one side of which is hard Aubrey limestone while on the other is soft Moencopie shale. In other words, when the lava was poured out the country was so far worn down toward base-level that the difference in the two kinds of strata was of comparatively little importance. At present, where these two formations lie side by side above base-level and are exposed to erosion, the shale is very rapidly worn away, leaving the limestone as an escarpment. At the time of the lava flows the junction of the two seems to have been so close to base-level that the hard and soft strata on the two sides of the fault were worn down to a level or only gently sloping surface, and lava from the downthrown side flowed across the fault line. This does not mean that the entire region was reduced to the lowest possible level, for near the Virgin river the lava after crossing the fault was soon checked by an escarpment of limestone rising two or three hundred feet with a fairly strong slope.

At Sugar Loaf, the third of the localities already mentioned, and on the Shivwits plateau there is evidence of a local base-levelling of a more pronounced type. Here the surface at the time of the lava flows previous to the recent faulting consisted of Moencopie shales. These are very soft rocks which, under present conditions of high altitude and consequently of active erosion, never form a level surface of any considerable extent. As soon as the protecting cap of Shinarump sandstone and conglomerate is removed, the shales are dissected into a regular bad-land topography and erelong melt away entirely. Yet under the lava flows there is an extensive flat surface of just such shales, which does not even correspond with the bedding planes of the rock, but bevels the strata at a slight angle, and so cannot be due to any particular layer of unusual hardness. Such a surface can only be produced close to base-level. As it is best exemplified in the Shivwits plateau which lies in the centre of Mohave county, Arizona, we shall hereafter refer to it as the Mohave peneplain.

Farther north between Toquerville, and Dry canyon, a lava flow some fifteen miles long and from two to three miles wide lies partly in the valley at the western base of the Bellevue ridge and partly high up on the top of the ridge. The two portions have been broken apart and displaced from one thousand to fifteen hundred feet by the recent Hurricane fault. The lava seems to have come from a group of craters near the northern end of the flow, and located in part on the upheaved and in part on the downthrown side of the fault. The basalt from these flowed southward down the Bellevue valley. On the west it was checked by

the foothills of the Pine Valley mountains, on the east it was limited by the upstanding Carboniferous limestone of the Bellevue ridge, over which as a rule it could not flow. In certain places, however, the lime stone pitches down so as to pass below the level occupied by the peneplain of that time. Wherever this is the case, the basalt spread out to the eastward and covered the bevelled edges of the softer strata that overlie the Carboniferous. The most marked example of this is two or three miles south of Dry canyon at an elevation of sixty-three hundred feet just east of the Hurricane fault (Fig. 7). Here the level surface on which lies the uplifted lava is composed of Moencopie shale, Shinarump conglomerate, Painted Desert shale and sandstone, and Kanab sandstone, all dipping strongly to the east. Where the same strata are exposed to erosion the hard Shinarump and Kanab form strong cuesta-like ridges

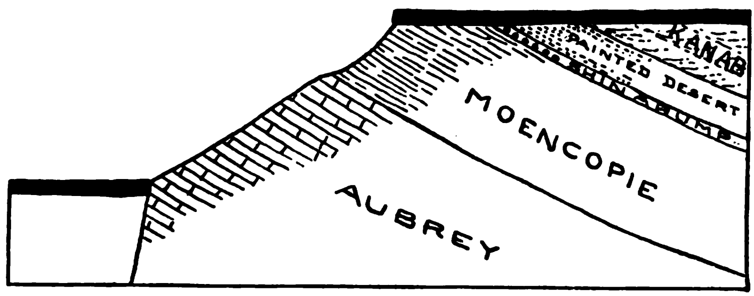


FIGURE 7.
Bellevue ridge four miles south of Dry canyon.

separated by valleys excavated in the soft Moencopie and Painted Desert (Fig. 3). Only under conditions approaching closely to baselevelling would it be possible for a level surface such as that beneath the lava to truncate smoothly strata of such varying hardness.

(3) PORTIONS OF THE ANCIENT SURFACE NOT COVERED BY LAVA. At the mouth of the Virgin canyon, as we have seen, lava seems to have flowed across the fault line from the downthrown side and to have been soon checked by an escarpment of limestone rising nearly four hundred feet. A reference to the illustration (Plate 3 B) shows in the middle of the picture a precipitous slope, the scarp of the modern Hurricane fault. This rises three or four hundred feet to a terrace a few hundred feet wide formed by the uplifted eastern portion of one of the lava flows. Behind this the ascent consists of rounded maturely dissected slopes of quite a different character from the youthful cliffs below

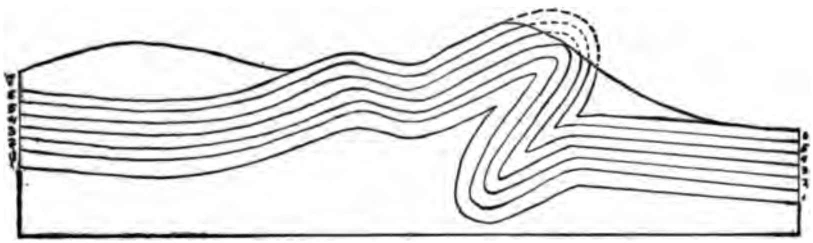
them and from any of the cliffs that are due to recent faulting. These slopes have been renewed and steepened by recent erosion, but nevertheless they are continuous with the surface under the lava and seem to be the product of the same period of erosion. If our interpretation is correct, the mature topography at the top of the escarpment is a battered remnant of that which prevailed before the plateau region was uplifted at the time of the last great faulting. West of the fault where the main body of the lava sheet now lies, soft sandstones and shales had allowed the reduction of the surface nearly to base-level; east of the fault relatively hard limestone produced a gentle escarpment rising to a plateau three or four hundred feet higher than the adjacent lowland, a Monadnock of Carboniferous strata in the Mohave peneplain.

A more perfectly preserved example of the ancient topography is displayed in the lofty plateau of Colob, a few miles beyond the northeastern corner of the area shown on our map. This forms a portion of the upheaved block east of the Hurricane fault, and lies at an elevation of from eight thousand to ten thousand feet. On the west it is bounded by a great escarpment, due in part to the old fault and in part to the new one, as will be explained later. To the south it is limited by the imposing Vermilion cliffs, nearly two thousand feet high, which here reach their greatest development. To the north and east it stretches away indefinitely, until it merges into other portions of Dutton's High plateaus, of which it may be considered a fair sample. Around the edges of "Colob," as it is locally called, the revived activity of erosion consequent on the last faulting has caused most energetic dissection, and steep cliffs, naked ledges, and profound canyons are the rule. In the centre of the plateau, however, the ancient pre-faulting topography is still preserved in broad vistas of gently sloping hills and dales, the finest of summer pasture for sheep and cattle. Sometimes for miles scarcely an outcrop appears. The relief, to be sure, is considerable, amounting to fully two thousand feet, and in certain places the hills might well be called mountains if that term could be correctly applied to an elevation having a distinctly non-mountainous structure of nearly horizontal strata. The maturity of the topography and its contrast to the youthful character of the peripheral regions are so marked that we seem forced to believe that it is the product, not of the present canyon cycle, but of the previous inter-fault cycle.

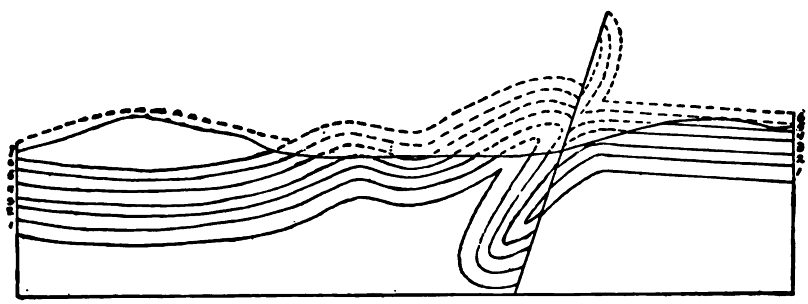
(4) THE NEW AND THE OLD FAULTS AT KANARRA. The escarpment which bounds the Colob plateau on the west shows the old fault and the new exposed under conditions where it is easy to compare their

FIGURE 8.

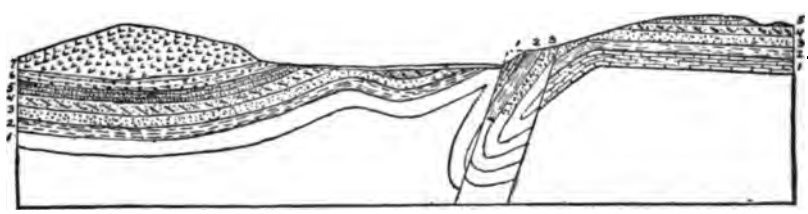
CROSS-SECTION OF THE HURRICANE FAULT NEAR KANARRA, LOOKING NORTH.
(From Journal of Geology.)



Ideal section after the early folding.



Restoration of section at the end of the inter-fault cycle of erosion. The dotted lines represent the section at the beginning of the inter-fault cycle.



Section representing present conditions. 1, Aubrey limestone; 2, Moencopie shales; 3, Painted Desert shales and Kanab sandstone; 4, Colob sandstone; 5, Cretaceous; 6, Tertiary; 7, Andesite.

topographic effect and hence to estimate their relative age. To the east at the top of the escarpment is the maturely dissected upland, to the west at the base of the slope is a broad intermont basin floored with waste brought down from the uplifted region around it.[1] The escarpment itself shows at the top the mature slopes of the undisturbed ancient surface; farther down these grow more rugged and ledgy under the influence of renewed erosion, and at the base is the straight step scarp of the modern fault. South of Kanarra these simple features are varied only by the texture of the rocks and the size of the streams. It is near this little Mormon village, however, that the old fault reappears after being concealed for many miles under alluvium and basalt. It will be remembered that the new fault here crosses the old one at an acute angle shearing off the western and southern portion. To the north both faults can be easily traced. The long slender wedge between them is composed of strata which were overturned at the time of the early folding and now lie in inverted order with a strong westward dip (see Fig. 8). Dutton speaks of the overturned fold and complicated fault at Kanarra as showing an exceptional movement (*a*, p. 29). Along the line of the old fault between these reversed strata on the west and the very slightly inclined normal strata on the east the slope of the escarpment everywhere diminishes, forming a slight terrace or even a little depression contouring along the slope. This is due to the fact that on both sides of the fault lie soft strata, while above them is the great mass of the plateau on the one hand and the cuesta-like ridges of the hard Aubrey limestone and Shinarump conglomerate on the other. Thus it happens that the old fault which geologically amounts to many thousand feet, has been entirely effaced geographically and is even replaced by a valley. More than this, the valley was not only worn out along the ancient fault line before the period of the second faulting, but was also filled in part with gravel, and on the gravel was poured out a lava flood. That the lava was poured out before the last faulting is indicated by the fact that it lies horizontally on what is now a hillside, but was then a valley floor. Moreover the erosion consequent on the uplift at the time of the later faulting seems to be the only competent cause for the dissection of the lava-covered gravel into flat-topped buttes, where the loosely cemented pebbles are protected from erosion by a sheet of basalt. The

[1] This plain lies at an elevation of about six thousand feet, and forms part of the divide between the interior basin and the Colorado river. It is so flat that several streams flowing out of the mountains are sometimes deflected northward to Sevier lake and sometimes southward to the Pacific ocean.

relation of the two faults at Kanarra indicates that they are of different age. The topography seems to show that one is ancient, the other modern, and that between the two there was a long period of erosion.

(5) Evidence of Prolonged Erosion in the Downthrown Block West of the Hurricane Fault. In the preceding paragraphs most of the evidence on which we have based our conclusions as to the amount of erosion during the inter-fault cycle has been drawn from the upheaved block east of the fault. If our theory is correct, the downthrown, or St. George, block on the other side ought to preserve much more perfectly the topography of the close of the inter-fault cycle, provided that this western block, too, has not since suffered elevation or depression. The slopes ought to be gentle and well graded; the valleys ought to be broad and waste-filled, and should truncate the underlying formations without reference to the attitude of the strata; and lava sheets ought to be almost undisturbed by the erosion which is rapidly dissecting into buttes the similar formations of the block upheaved by the second faulting. If, however, the block was depressed at the time of the last faulting, although we should expect to find these same topographic features, some of them would be drowned under new deposits of waste. If, on the other hand, the western block was somewhat elevated at the time of the faulting, we should look for a combination of the mature topography of the inter-fault cycle and the youthful topography of the present canyon cycle. The relative amounts of the two would depend largely on the amount of uplift, the lapse of time, and the texture of the strata. As a matter of fact, it is just such a combination of mature and young topography that we find all along the eastern border of the Basin Range province at the foot of the Hurricane and Grand Wash faults.

For example, where the Virgin river, after crossing the Hurricane fault, emerges from its limestone canyon, it enters a region of which the surface is now basaltic lava. In this the river has cut a steep-sided trench a hundred feet deep. In the sides of this young canyon and to a greater extent in the sides of the similar young canyons of Ash and LeVerkin creeks, which here join it from the north, an old surface of sandstone is disclosed. The maturity or even old age of this surface is borne witness to by its extent as indicated by the breadth of the deposits of gravel and beds of cobbles which lie upon it and are in turn covered and preserved by lava. Still further evidence of its age is found in the fact that it truncates highly inclined strata without paying any attention to their attitude or relative resistance. In this it is like the rest of the Mohave peneplain, of which it forms the northern part.

West of Leeds and Harrisburg, at the southwestern base of the Pine Valley mountains, we have more marked remnants of the ancient topography in the form of long, gently sloping grade plains which are now mere strips stretching forward from the edge of the mountains. As one looks westward from Leeds, most of the view consists of naked hills with steep rocky sides of red, white, and brown sandstone. The harder layers stand up as cuesta-like ridges across the spurs which run out from the mountains toward which the strata dip; the softer ones form depressions separating these lines of elongated knobs, which, if united, would form cuestas. Both alike are almost bare of soil, and support scarcely any vegetation except sagebrush and cactus and a little desert grass. Here and there, however, almost parallel to the present valley floors although several hundred feet above them, run long but broken lines of green, sloping gently from the mountains toward the river. They seem to be remnants of the former mature topography, not yet consumed by the revived erosion of the canyon cycle. Their verdure is in part merely apparent, because they are level and hence are seen foreshortened, while in part it is real because of the fact that they are well graded and hence have a depth of soil sufficient to support a growth of juniper trees.

Other examples of a similar kind are found near St. George and along the South Fork of Ash creek near Bellevue. In the former place, which will be described at some length below, the erosion of the present cycle has gone so far that but little remains of the old topography except those portions that are buried under lava flows. These form mesas, and along their borders are exposed most excellent sections of the ancient topography, showing conclusively its mature character. The South Fork locality, on the other hand, lies near the headwaters of the stream, and in a place where lava flows a little farther down Ash creek have prevented deep erosion. Accordingly here the features of the former cycle are well preserved. They take the form of broad well-graded slopes lying between sharply incised canyons of no great depth which represent the erosion of the present cycle.

Turning now to some places at a greater distance from the Hurricane fault, but still belonging to the downthrown St. George block west of the displacement, we find that near Black Rock, forty-five miles southwest of Toquerville, the broad flat notch at the divide between the Grand wash and the Virgin displays for the most part a mature type of topography, even where there is an ascent of a thousand feet to the Shivwits plateau on the east and to the Virgin mountains on the west. Twenty-five miles down the Grand wash the main features of the topography are

still mature so far as the St. George block is concerned. Here and there, however, are evident indications of renewal, such as a shallow canyon cut through a lava flow, or the shallow valleys which all the streams have cut in the heavy gravel deposits which fill the bottom of the wash and therefore belong to a time anterior to the last great faulting. Thirty miles farther southwest — that is, about one hundred miles southwest of Toquerville — at Scanlon's, or, as it is now called, Gregg's ferry, fifteen miles below the mouth of the Grand canyon, the same feature is seen. The Colorado river has intrenched itself to a depth of about two hundred feet in heavy gravels which at an earlier time must have filled its broad valley to a considerable depth. The extensive valley floors, grade plains, and the other forms of mature topography west of the Hurricane all seem to indicate that at the end of the inter-fault cycle the topography of the St. George block was of the same type as that which we have already described from smaller samples preserved in the uplifted block east of the Hurricane. In both blocks there has been a renewal of erosion, although it is much more marked in the eastern block. The connection between these renewals will be considered later.

SUMMARY. All the lines of evidence which we have been pursuing lead to the same conclusion. The unequal recession of cliffs on the two sides of the Hurricane fault; the bits of ancient surface preserved under lava flows; the mature topography of the Colob plateau; the contrast between the old and new faults at Kanarra, and the grade plains, mature topography, and broad surfaces covered with gravels west of the Hurricane — all point to a long period of quiet erosion between the first and second faultings. At the end of this inter-fault cycle of erosion the whole country was physiographically mature or even old. Certain regions of soft strata, chiefly near the Colorado river, had been reduced very nearly to base-level forming the Mohave peneplain.

Attitude of the Land, and Topography at the End of the Inter-Fault Cycle.

In our study of the borderland between the Plateau and Basin Range provinces we have already found two critical points, and now have come to a third. The first was at the end of the long cycle of deposition just before the strata were upheaved, flexed, and folded; the second was at the end of the time of quiet, when flexing had ceased and the earlier faulting had not yet begun; the third is at the end of the in-

ter-fault cycle of erosion, just before the beginning of the last great faulting.

The exigencies of language and the necessity of brevity often oblige us to speak of periods of faulting and folding as though they were distinct from those of erosion. According to the old cataclysmic idea, this was indeed the case. We may illustrate this graphically by a diagram in which the course of time is represented by horizontal distance, while the relation of any given stratum to sea-level is represented by vertical distance. The cataclysmic theory supposed that periods of uplift or other tectonic movement were so sudden and paroxysmal that in such

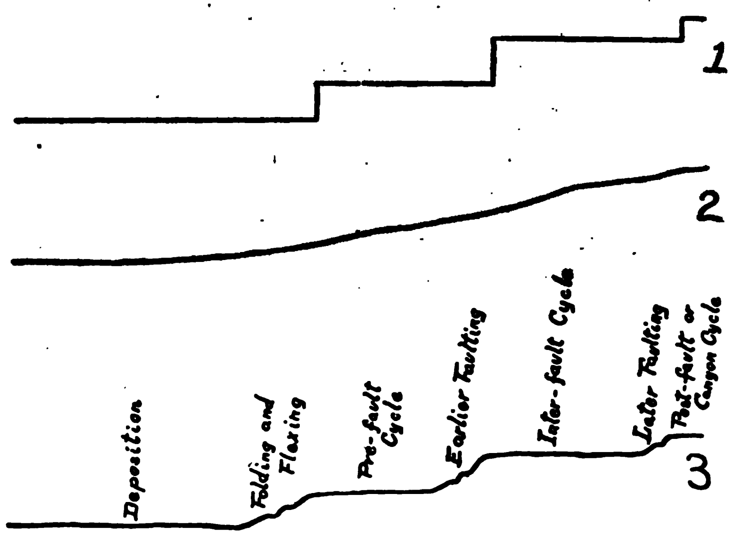


FIGURE 9.

Diagrammatic scheme of cycles. 1, Pure cataclysmic view; 2, Pure uniformitarian view; 3, Eclectic view.

a diagram (Fig. 9) they might fairly be represented as vertical lines, since the time element involved was thought to be negligible. A similar diagram representing the opposite or uniformitarian view shows absolutely no vertical lines, and relatively few that are perfectly horizontal. Changes were supposed to take place so slowly that there was comparatively little chance for absolute rest, and none whatever for sudden transformations. The modern or eclectic view is a combination of these two. It supposes the existence of distinct periods of essential rest separated by longer or shorter periods of unrest, during which there

is upheaval or depression accompanied by flexing, folding, or faulting. These movements begin and end slowly. They are of considerable duration, and are varied by minor times of very rapid change or of almost complete quiet. Erosion proceeds as before, and is active or inactive in the normal fashion in proportion to the elevation of the country on which it works. As applied to the Plateau province, this view of earth movements is graphically illustrated in the last of the three diagrams in Figure 9. In this it is seen that since the end of the long Mesozoic period of deposition there have been three periods of uplift separated by longer periods of quiet. The former, however, were not continuous but were broken up into many episodes, when short periods of rest followed those of violent movement. Erosion continued unchecked at all times, but was divided into three distinct cycles.

The initial stage of what Davis (*c*) has called a geographical cycle is a period of uplift during which erosion is revived and a region becomes young. The remaining stages of the cycle are carried to completion during the succeeding period of comparative rest. An ideal cycle involves not only the initial uplift whereby the country becomes young, but also a far longer time of little movement during which the relief passes through all the stages of maturity and is finally reduced to the featureless peneplain of extreme old age. In another sense, however, the term cycle implies not the whole, but only a part of this long lapse of time. It is any period of erosion which begins in a movement of uplift and is brought to a close by another tectonic movement either of elevation whereby erosion is revived and a new cycle introduced, or of depression whereby erosion is brought to a standstill by the encroachment of the sea. Such interruptions may occur at any time, even in early youth, but the interval from the beginning of one to the beginning of another is still a cycle. The word "cycle" is used in a sense analogous to that of the word "life," and like it may be used in two distinct but complementary ways. Life in one signification is the complete existence of a normal organism during which it passes from infancy through youth, maturity, and old age to death. The life of man in this sense is seventy years. In another sense life is merely the actual period of existence of a specific organism. An animal whose life in the first sense of the word is fifty years, may die the day that it is born, but nevertheless we say that it has finished its life. A cycle in the first sense is ideal and can never be realized, since infinite time would be required to reduce any land mass to the condition analogous to death, that is, to a plain at absolute base-level. In the second sense any region that is subjected to erosion during

a definite period, no matter how short, passes through a cycle and can be described in terms of age and development.

Referring again to the diagram, it will be seen that the three periods of erosion that are discussed in this paper — the pre-fault, inter-fault, and post-fault or canyon cycles — are not rigidly limited by hard and fast boundaries. They shade off into one another, and no one can say exactly where one ends and the other begins. Nor can we say that in any two of them erosion has proceeded to exactly the same extent, for the two cycles that have come to an end were interrupted long before they had been carried anywhere near ideal completion, and the present cycle is still very little advanced. In certain places, to be sure, the inter-fault cycle had proceeded so far that the country was in the final stage of development, old age, but elsewhere either because the strata were harder or were less exposed to attack, the same length of time had only been sufficient to reduce it to the middle of maturity. Yet both these types fit perfectly into the cycle scheme of treatment. So, too, if to-day in its extremely youthful condition the plateau region should sink below sea-level, the canyon cycle would still have all the attributes of a true cycle in the second of the senses defined above.

One further feature illustrated by the diagram deserves attention. A period of faulting, like a cycle of erosion, seems to involve a definite series of systematic changes. From a feeble, perhaps imperceptible beginning, it, theoretically at least, passes through a period of increasing strength until the rate of dislocation reaches a maximum. It then becomes gradually weaker and gradually dies out. If it would not lead to confusion, these stages, as well as those of the cycle, might fitly be termed youth, maturity, and old age; but it must be clearly borne in mind that when faulting has attained old age or death, the cycle of erosion that it introduced may still be in early youth or at most can only be in maturity.

In considering any period of uplift it is necessary to take into account not only the processes and changes which are represented by the vertical component of the diagram (Fig. 9), but also of those features which are represented by horizontal space. Accordingly a complete treatment of a displacement such as that of the Hurricane fault involves three main heads. (1) The first is the condition of the country before the faulting. Were the strata horizontal or plicated? Was the surface above or below sea-level? If it was above sea-level, had it been subjected to little or much erosion? and are any traces of the pre-faulting topography preserved from which we can reconstruct the whole? (2) The second con-

sideration is the displacement itself, — its measure and plan, horizontally and vertically, and its date. This part of the subject is the only portion that is commonly treated systematically and fully. It represents the vertical component of the diagrams of Fig. 9. It is more definite and more easily worked out than the other divisions of the subject, and can be more easily stated, but it is of no greater importance. The case is analogous to that of mountains where the ridges and peaks, the culminating portions, are easy to apprehend and have been mapped and described again and again, while the slopes in spite of their varied form and great extent are passed over without minute observation and are almost never well described. (3) The third division involved in a treatment of faults is the changes that have taken place since the displacement. It is usually tacitly assumed that a discussion of these is necessary, but the subject is commonly dismissed in a few sentences, as though it were something that every one could picture for himself. Yet such is by no means the case. Definite, careful statement is as essential here as it is in the description of the fault itself.

In our account of the first folding and of the earlier Hurricane fault we have briefly considered these three aspects. In what follows we shall treat the later faulting in the same way, but with more detail. The topographic condition of the country has already been considered under the head of the inter-fault cycle of erosion. It is further necessary to restore the whole region to its former attitude with respect to sea-level, including the relatively downthrown as well as the uplifted portions. We shall begin with the most elevated block, which was probably also the one that last suffered movement, and shall restore the different parts to their places in an order inverse to that in which they were displaced. The first step in this process is to lower the upheaved block east of the Hurricane fault until its lava sheets match those of the downthrown block to the west. This, however is not enough, for, as we shall see later, a very considerable part of the uplift that introduced the canyon cycle took place along the Grand Wash fault. If the region disturbed by this latter displacement is restored in the same manner to its former position, we find that the southern end of the Shivwits plateau is thereby lowered from its present elevation of six thousand feet to only one hundred or fifteen hundred feet. At the northern end of the Grand Wash fault, however, in the valley of the Virgin, the Shivwits plateau, of which the lowest points are now at an elevation of from twenty-five hundred to three thousand feet, is not depressed at all by restoration, while the northern part of the Uinkaret plateau just to the east of the Hurricane

is depressed but three hundred feet at the least and fifteen hundred at the most.

Even yet, however, we have not restored the country to as low a level as the facts seem to demand. As we have seen in a preceding section (p. 235), the valley of the Virgin river southwest of Toquerville shows signs of a renewal of erosion, which was probably associated with the disturbances attendant on the recent faulting. The only satisfactory explanation of this seems to be that the western block was upheaved in sympathy with the eastern block, but to a much less extent. Along the Colorado river and Grand wash there are similar indications that the western block was uplifted somewhat, although perhaps less than at Toquerville. For the sake of stating the problem in a quantitative form, let us assume that the farther depression required by the renewed erosion of the western block, in order to restore the region to the attitude which it held at the end of the inter-fault cycle, amounts to five hundred feet along the Colorado river, and one thousand feet near Toquerville. These figures are only approximations, and can be doubled or halved without affecting the verity of our presentation. At Toquerville, then, according to this hypothesis, the northern end of the Shivwits plateau stood at an elevation of from fifteen hundred to two thousand feet. To the southward it descended gently, until at the Colorado river the elevation of the Mohave peneplain was only five hundred, or at most one thousand feet. The strata, which now dip gently to the north, must then have dipped a little to the south, and near the Virgin river there must have been a faint anticlinal arch, with an east and west axis. The Uinkaret, Kanab, and Kaibab plateaus, to the east, must have stood very low also, since there is no evidence of any marked modern break between them and the Shivwits plateau, and since the Grand canyon has been cut in them to a depth as great as in the Shivwits, during what appears to be exactly the same length of time. To the northwest, however, the Colob plateau, and probably the rest of the High Plateaus seem, as measured by the amount of faulting, to have stood at an elevation of about six or seven thousand feet, only three thousand feet lower than at present, but it may be that these figures will require modification. The topography of the plateaus as seen in Colob, and in those described by Dutton, is more subdued and more mature than would be expected in a region standing at so great an elevation, within a few miles of a lowland four thousand feet nearer to sea-level. It is possible that a further study of this comparatively little known region will show that the amount of uplift at the time of the last faulting was rather more

than three thousand feet, stated above. Accordingly in the ideal (Fig. 10), we have drawn the pre-faulting surface of Colob four hundred feet below the present level. The Pine Valley mountains, on the other hand, certainly stood at a height of seven or eight thousand feet, and then, even more than now, dominated the landscape for scores of miles on every side.

If the steps of our reasoning thus far have been correct, the master stream of the region, the Colorado, must at this time have been a strong but thoroughly graded river, with a descent of from one to two feet per mile. Such a stream would probably have ceased to deepen its channel, because the heavy load which it received from the highlands would be deposited in the lowlands, and would act as a cloak protecting the underlying strata from further erosion. In this way the river would be held for a long time at nearly the same level, and would have an opportunity to swing over a wide valley floor, although the strength of the current would prevent the formation of meanders. The tributary streams would act in the same way in their lower courses, and thus the Mohave peneplain would be formed. Farther toward their heads we know that the streams flowed in more pronounced valleys, which had a depth of hundreds of feet, although the sides were of very moderate slope and thoroughly graded. In the larger valleys hard and soft strata alike were evenly truncated without reference to their texture or attitude. In the middle

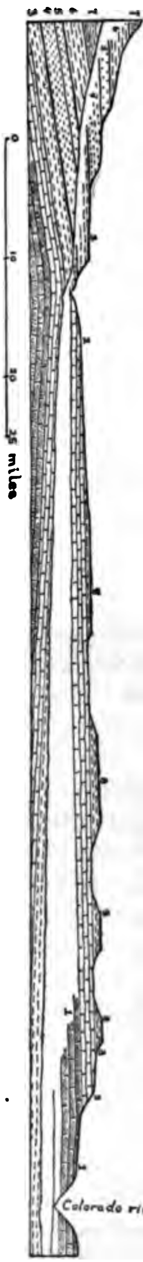


FIGURE 10.

North-south sections, from Colob to the Colorado river, showing conditions before and after the later faulting. The base-line of the sections is at sea-level. The lower section represents pre-faulting conditions; the upper one shows present conditions. 1, Red wall limestone; 2, Aubrey; 3, Moencopie and Shinarump; 4, Painted Desert and Kanab; 5, Colob; 6, Cretaceous; 7, Tertiary.

regions the soft formations were reduced to a plain which truncated the strata at an elevation determined by the local base-level. The harder, more resistant formations stood up as terraces or plateaus where they were horizontal, and as ridges or cuestas where they were tilted. In the most elevated regions the relief was very marked. In a highly resistant mountain massif, such as the Pine Valley range, standing at an elevation of eight thousand feet, there were fairly deep valleys which nevertheless did not penetrate far into the centre of the lava mass. In a plateau such as that of Colob, where relatively soft strata stood at an elevation of from five to seven thousand feet, advanced dissection was the rule, and we find great valleys penetrating far into the interior and having a relief of several thousand feet.

Two rather unexpected results arise from this restoration of the country to its pre-faulting condition, and for neither of them can we offer an adequate explanation. One is that the Virgin river, if it was then located where it now is, flowed along the broad, flat arch of a gentle anticline. It is possible that the river was shifted to its present position after the anticline was flattened out, but of this we have no evidence. Another point that attracts attention is that the anticline lies directly in line with the most massive portion of the Pine Valley lava mass, and is almost a continuation of the line where the folds of an earlier date flatten out into simple monoclines. Whether these three things are causally connected or not, is wholly unknown. Their relation suggests that the lava of the mountains acted as a great buttress, around which the sedimentary strata have been bent and plicated, just as in a tidal estuary ice is bent around the pier of a bridge.

Before leaving the subject of the condition of the country just prior to the second faulting, let us get a bird's-eye view of the whole region. From the top of the lofty Pine Valley mountains an observer would have seen to the southwest, west, and north, the low ridges of the southern part of the Basin Range province — ancient mountains, well dissected and mature, and presenting nearly the same appearance as to-day. To the east were the High Plateaus, lying considerably lower than at present, and everywhere carved into broad valleys, from which rose rounded hills of horizontal strata to a height of two thousand feet, more or less. The cliffs and canyons which are now so striking did not then exist, but in their places were long, gentle slopes, covered deeply with soil and probably with vegetation. Still farther around the horizon from the east to the southwest, the observer would have seen a smooth monotonous expanse, the Mohave peneplain, sloping slightly away to

the Colorado river, and unbroken by any elevation more prominent than a subdued escarpment a few hundred feet high. Nowhere in all the broad horizon was there anything sharp or abrupt in the relief. Everywhere maturity and old age were the rule, — a maturity of strong but unobtrusive outlines, whose mountains were domes and whose valleys were broad basins filled with gravel; an old age where relief had almost vanished.

Lava Flows.

Having reconstructed the topography as it existed at the end of the inter-fault cycle, we must put off the discussion of the last faulting long enough to mention a few facts connected with the lava flows which are so important as a means of preserving the ancient surface and of measuring the extent of recent displacements. When at last the time arrived for the land to wake from its long rest and once more begin an active life of uplift and growth whereby it might enter a new cycle and renew its youth, the first warning of impending change came in a series of lava flows, the precursors of a long line of which the last was poured forth but yesterday. Our observations agree with those of Dutton and others in showing that lavas were often ejected many times from what seems to be the same vent. In some cases there appears to have been no great interval between successive flows, since there is no noticeable evidence of weathering and erosion to differentiate them. In the fault scarp above Bellevue, for instance, a section has been exposed in which are at least ten thin sheets of basalt that seem to have been poured out in comparatively rapid succession. At St. George, on the other hand, is one of the best examples of a very different type (Fig. 11). Just west of the town rises a broad flat-topped mesa of Painted Desert and Kanab sandstone capped at an elevation of five hundred and fifty feet above the town by a sheet of basaltic lava, *A*. On the east side of this, about three hundred and fifty feet below the top, lies a terrace a few hundred feet wide which, like the mesa, owes its preservation to a cap of basalt, *B*. The general level of the country on either side is now more than two hundred feet below the terrace. On the valley floor to the west is a third sheet of lava, *C*. All three of these flows seem to have come from a point a few miles to the north, although it is not known whether they are all derived from the same source. They represent the great difference in age which prevails among the products of volcanic eruptions, even though all may rightly be called

recent. The oldest lava sheet, *A*, appears to have been poured out on the graded surface which characterized the country at the end of the inter-fault cycle. Then the general uplift which seems to have accompanied or perhaps preceded the recent faulting and to have raised the whole region — the western as well as the eastern side of the fault. Erosion at once became active, and valleys were cut to a depth of three hundred and fifty feet on one or both sides of the lava sheet. Then, before the uplift had been completed, or at least before the renewed erosion which it occasioned had reached a condition of equilibrium, another stream of lava, *B*, flowed down the valley east of the first. Again valleys were worn away, this time to a depth of nearly three hundred feet, and in very recent times a third lava flow, *C*, poured down

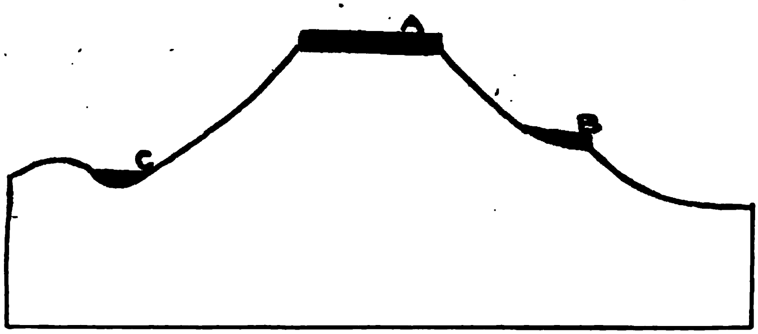


FIGURE 11.
Lava terraces at St. George.

the western valley. Since that time there has been further erosion along the main drainage channels, so that the first lava flow now stands some eight hundred feet above the neighboring streams. Elsewhere are even more modern lava flows, showing absolutely no sign of erosion, so that we have good evidence that there has been a continuous series of volcanic eruptions extending throughout the whole period that may be geologically called recent.

The difference in elevation at St. George between the Virgin river and the most elevated lava sheet gives a minimum measure of the amount of uplift to which the downthrown block west of the Hurricane has been subjected. This amounts to eight hundred feet. As the river can hardly have flowed more than one or two hundred feet below the general surface at the end of the inter-fault cycle, the country must then have

stood at least six hundred feet lower than now. If, however, the river had now cut down to as low a level as it then occupied, it ought to be equally well graded, but this is by no means the case. Accordingly we are justified in assuming a greater uplift than six hundred feet. In a preceding section we have put this at one thousand feet as an average for the whole region north of the Shivwits plateau. In certain places it may have been greater. A study of the map (Arizona, Mount Trumbull sheet) shows that where the Virgin river cuts through the Virgin mountains ten or twenty miles southwest of St. George it flows in a precipitous canyon of very young aspect. The gorge is incised to a depth of fifteen hundred feet in a maturely dissected mountain mass from which the young valley is almost as sharply distinguished as the Colorado canyon is from its plateau. A conclusion based only on map study cannot be final, but we believe that future observation will show that parts of the St. George block have been uplifted over fifteen hundred feet. This fact has an important bearing on the recent displacement which we shall now discuss.

The Later Faulting.

In all the foregoing consideration of the earlier faulting, the prolonged erosion, and the lava flows we have been constantly obliged to refer to the later faulting, and have spoken of it as though it were a proved fact for which we had already presented the evidence. So much, indeed, has been said that it is here necessary merely to summarize the facts, to discuss the offset by which the displacement passes from the Hurricane to the Grand Wash faults, and to point out the bearing of these facts on the history of the Grand canyon of the Colorado.

The displacement by which the Colorado plateaus were uplifted and by which the cutting of the Grand canyon was inaugurated began as a general uplift of the whole country. This is shown by the renewed dissection in the blocks west of the faults as well as in those east of them, proving that the former were uplifted with the latter, though to a less extent. Soon, however, the eastern portion of the country, which is now known as the Colorado plateaus, broke away from the western Basin Range portion and was uplifted at a more rapid rate. The displacement between these two blocks, so far as we have studied it, consists of three parts: (1) the later Hurricane fault, (2) the Fort Pierce monocline, and (3) the later Grand Wash fault. The evidence of the two faults lies chiefly in numerous displaced lava sheets. Some

of these are broken sharply in two as at Bellevue, at the mouth of the Virgin canyon, and at Sugar Loaf along the Hurricane, and at the southern end of the buttes in the middle portion of the Grand wash. Others, such as those at Toquerville on the Hurricane and at the northern end of the buttes in the Grand wash, are highly flexed into attitudes which liquid sheets of lava could not possibly assume, and therefore must have been bent into their present position by movements of the crust. In addition to this evidence from lava flows the fault scarps themselves show signs of being very recent. They are almost always ungraded and precipitous, and run across country with utter disregard to structure or drainage. A third proof of recency lies in the fact that the strata on the two sides of the modern faults match perfectly when restored to the level that they occupied before the faulting took place. In regions where faulting took place long ago the outcrops on the two sides have retreated at unequal rates and do not match.

The relation of this recent faulting is well understood in the case of the Hurricane fault, where, as we have seen, the topographic results of the earlier faulting were almost entirely effaced during the long inter-fault cycle. The later faulting followed closely the general line of the other, but, contrary to what would be expected, often diverged from it slightly for long distances. Thus, though the two run closely parallel, they do not coincide, and sometimes cross one another as at Kanarra. In the Grand Wash fault the relation between old and new is not so clear, because, on account of the inaccessibility of the region, our knowledge of it is very slight. Our own observations applied almost entirely to the distinctly modern faulting. Gilbert, however (*a*, p. 54), gives an east and west section along the mouth of the Grand wash which shows that the total displacement is decidedly greater than that which our observations show to be due merely to the new fault. The logical inference is that there was an earlier Grand Wash fault corresponding to the earlier Hurricane fault. Davis (*b*, p. 147), on the basis of facts stated in Dutton's atlas and monograph, states that "while a monoclinal slice of the Trias is preserved along the thrown [western] side [of the Grand Wash fault], there is no Trias on the heaved Shivwits block for fifty miles. The Trias must have once extended eastward beyond the line on which the fault was broken, and the uplifted eastern extension of the formation must have been worn away after the faulting." The erosion which could remove such an extent of strata from the uplifted block must have required far more time than has elapsed since the

recent faulting. Accordingly Davis (*b*, p. 148) infers that the Grand Wash fault, like the Hurricane, is double, one part being old, the other new. Nothing that we saw contradicts this so far as the southern part of the displacement is concerned close to the Colorado river. In the northern part of the Grand wash, however, we saw evidence of only one displacement, and that was of recent date. Apparently the old fault was of small dimensions compared to the modern one, and died out some fifteen or twenty miles farther south.

Taking up once more the recent displacement as a whole, we find that at Kanarra, the northern limit of our study, it is a true fault with a throw of two thousand feet or more. This decreases toward the south, very slowly at first, but later quite rapidly, until at Toquerville it passes into a monoclinal fold by which the lava sheet of Toquer hill is bent steeply upward some eight hundred feet. In the neighborhood of this hill the displacement is complicated by a number of small fractures, and is set off about three miles to the east in *en echelon* fashion. The amount of displacement continues to decrease until at the point where the Virgin river crosses the fault it amounts to only three hundred feet. Here, it will be remembered, lay the axis of the gentle anticline of the inter-fault cycle. Farther south the displacement again increases for ten or fifteen miles until it amounts to fifteen hundred feet. It then decreases, and south of Fort Pierce almost wholly disappears along the line of the Hurricane. This does not mean, however, that the displacement is lost. It merely turns from a north and south course and goes southwestward. Instead of being a sharp fault it takes the form of a long gently sloping monocline which descends toward the northwest. The northern limit of this slope lies a few miles south of the Virgin river; its southern limit extends from south of Fort Pierce to Black Rock. At the latter point the line of displacement again turns south, at first merely as a syncline and then as a true fault, the throw of which increases until at the Colorado river it is over five thousand feet. Black Rock is a central point, on every side of which there was uplift. To the south and east the strata were uplifted smoothly and form part of the upheaved plateau block. On the other sides they were uplifted in the form of a very flat cone one-third of which is replaced by the horizontal strata. It is as though most of the plateau block had been cut apart from the St. George block, but this one part remained attached, and when the eastern block was lifted up it pulled a corner of the western block up with it. The deep cutting of the Virgin canyon where that river passes through the Virgin mountains a dozen miles north of

Black Rock seems to indicate that in this portion of the St. George block such an extra uplift took place.

The relation between the upheaval of the Colorado plateaus and the cutting of the Colorado canyon has been explained time and again. Previous to the faulting the river flowed close to the level of the land surface as a whole. Its course at that time may have been in general consequent, as Davis has pointed out (5, pp. 158–167), but as yet we cannot fully restore the topography and structure of the entire region previous to the last faulting, and so cannot be certain on this point. When the plateaus were uplifted the rate of motion was so slow that the Colorado was able to intrench itself without appreciable change in its location, although the slight relief of the Mohave peneplain would not have been sufficient to prevent the river from shifting northward toward the Virgin had the uplift been very rapid. As it was, the Colorado cut for itself a deep trench along a course which, however consequent it may have been in the inter-fault cycle, seems to be strictly antecedent so far as the present canyon cycle is concerned.

Minor Faults.

In addition to the great faults along the border between the Plateau and Basin Range provinces, there are two minor faults in the vicinity of Toquerville. In both of these, as in all the known displacements of the region, the uplifted portion lies on the eastern side. The age of these is probably the same as that of the neighboring major faults, since they present what appear to be the same characteristics in respect to amount of dissection, agreement of outcrops on the two sides, and relation to the pre-faulting topography.

One of the two faults lies in the St. George block, a short distance east of the town of Washington. Its course is south-southeast for about ten miles from the foot of the Pine Valley mountains to Fort Pierce. Its northern end was not closely examined, but toward the south it was seen to lessen gradually until it passed into a well-rounded anticline, which in turn seemed to flatten out entirely where it meets the Fort Pierce monocline nearly at right angles. The fault is best exposed close to the Virgin river, where its throw is at a maximum. It here crosses the diagrammatic breached anticline of Leeds (p. 219), and has dropped the west side so far that for a distance of two or three miles the Shinarump ridges are buried in silt brought down by the river. An interesting feature of this displacement is that its point of maximum throw lies

very nearly in line with the point of minimum throw of the Hurricane fault. It may be a purely accidental coincidence, but as the main fault increases both north and south of this point to its normal throw the smaller sub-parallel fault decreases.

The second of the two minor faults lies in the Colob plateau, one of the loftiest portions of the upheaved eastern block. It trends a little more to the east than does the main fault, which here trends north-northeast. Toward the south it swings around still more to the west and dies out. In the escarpment of the Hurricane fault just north of Dry canyon a mild syncline appears, which seems to be the last remnant of the Colob fault. Along the line of maximum displacement, which amounts to seven or eight hundred feet, runs the upper part of LeVerkin creek for a distance of two or three miles. On the west of the stream the downthrown block, which might much better be called the less uplifted block, rises three hundred feet or more in steep but graded slopes covered with vegetation. On the east its edge presents a precipitous cliff of naked red sandstone which rises a thousand feet and is capped by a band of white, the Colob sandstone, and a band of green, the luxuriant vegetation that flourishes on the top of the well-watered plateau. A few miles from its source, LeVerkin creek leaves the line of the fault and plunges through the uplifted block in a chasm of profound depth and exceeding narrowness. The brevity of our visit to this region gave an opportunity for nothing but a hasty reconnaissance. It sufficed, however, to show that the tilted block between the Colob fault and the main Hurricane presents a type of topography different from any that we have elsewhere encountered. Here alone we find ponds, small sheets of water which during the rainless summer have no visible outlet. They lie in longitudinal valleys which seem to be of subsequent origin, as they run north and south parallel to the prevailing strike of the whole region whose strata here dip to the east. The present drainage, however, is largely consequent on the recent faulting, and seems to have no relation to the little basins that lie athwart it. In our brief traverse of the region we got the impression that at the time of the Colob faulting this block was tilted in such a way that an old subsequent drainage was entirely destroyed and a new consequent system inaugurated. Here and there, however, the old valleys were warped or dammed in such a way that they formed little basins between the headwaters of the younger streams. This region, together with the adjacent portion of the Hurricane fault north and south of Kanarra, and the neighboring Cretaceous with its abundant coal and fossils, affords a fine

field for a summer's geological study. Not only are there most interesting problems to be worked out, but there is the finest of scenery and a delightfully cool invigorating climate, utterly different from the sultry desert of the lower plateaus and valleys.

The Post-Fault or Canyon Cycle of Erosion.

The Normans relate an Indian tradition that long ago there was snow all the year round on the Pine Valley mountains, although it does not now come until November and is gone in June. Also, the valley of Ash creek was smoother than now and had no canyon: a great flood came and washed it out. Whether these are pure Indian traditions or an adaptation of the remarks of some early white explorer, we could not ascertain. If it is the former it is highly significant, and even if it is the latter it is essentially true, though less interesting. The canyon cycle must include at least the latter part of the glacial epoch, although no traces of glaciation have been noticed in our immediate district. It certainly has witnessed the change from the relatively smooth topography of the inter-fault cycle to the rough topography of the present. How much of this change occurred after man appeared on the earth has not been determined, but erosion proceeds so rapidly in this naked country that it is quite possible that a considerable portion of the work of the last cycle has been done since the first human inhabitants settled here.

The work of the Canyon cycle has consisted chiefly of the removing of weak strata that were formerly below sea-level, the cutting of deep canyons, and the steepening and renewal of cliffs. All these features are illustrated in the accompanying diagrams (Fig. 12), in which *I* represents the conditions previous to faulting, and *II* those of the present. In the first sketch, the Carboniferous series, *A*, and the overlying Moencopie shales, *B*, had been reduced to a peneplain, the surface of which is shown by the line *HI*, and on this had been ejected a lava flow, *G*. Farther north the same soft shales were protected by the hard Shinarump, *C*, with the result that there was a long gentle slope from the peneplain upward. Among the higher strata the soft Painted Desert series, *D*, and the hard Kanab sandstone, *E*, formed another slope of equally gentle ascent rising to the upland, *F*, of Colob and Cretaceous strata. At *H* and *I* were two rivers flowing toward the west in insignificant valleys. When the country was uplifted to the position which it now occupies, rapid changes began, which up to the present have gone

far enough to produce the young and vigorous topography of *II*. The hard Carboniferous strata, *A'*, have been but little affected except in the immediate river valleys, where deep narrow canyons, *I'* and *H'*, have been cut with very precipitous sides. The overlying soft strata, *B'*, have been entirely stripped off except where they are buried under lava and form mesas, *G'*, or where they are protected by the Shinarump, *C'*. In the same way the Painted Desert strata, *D'*, have been removed, and the overlying hard Kanab, *E'*, forms cliffs. To-day these cliffs are rapidly retreating but erelong talus from the upper hard layers will so cloak the lower soft layers that the slopes will become more moderate and the retreat of the cliffs much slower.

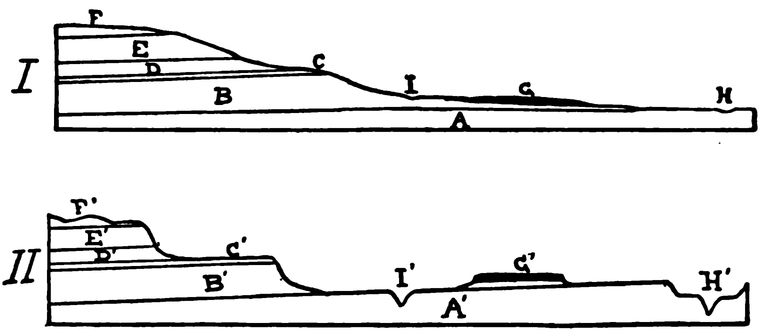


FIGURE 12.

North-south sections to show the work of the present cycle.

The best example of the stripping of soft strata is the great Carboniferous platform, in which is cut the canyon of the Colorado. Here, over an area of hundreds or even thousands of square miles, a few hundred feet of Moencopie shales have been stripped off, as is shown by the unconsumed patches remaining here and there, and by the larger masses preserved under lava caps. Although the most notable feature of the cutting of canyons is the Grand canyon, others, such as that of the Virgin river, are worthy of mention. An interesting case is that of Ash creek, which now flows in a shallow canyon at the foot of the Hurricane fault north of Toquerville. As this is part of the downthrown block, the amount of cutting has naturally been less than in corresponding cases on the other side of the fault. The notable feature, however, is that a short distance west of the present canyon is another of about the same size which is now dry and lies on the crest of an arched sheet of basalt

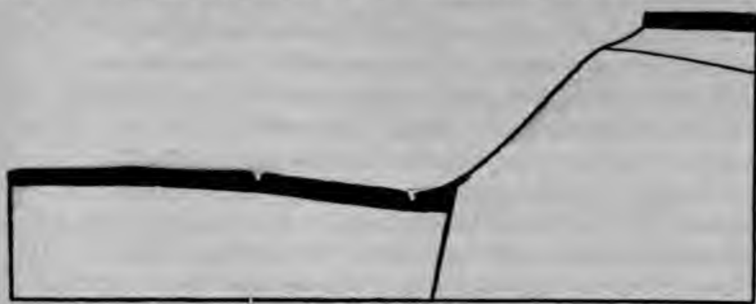


FIGURE 13.
The canyons of Ash creek, near Toquerville.

(Fig. 13). Apparently Ash creek cut the latter canyon before the last faulting, although possibly after the premonitory upheaval. At the time of the faulting the lava sheet was bent and the creek was tipped out of its old channel to the recent one. Renewed cliffs are everywhere the rule, although the most striking examples are the far-reaching lines of the great Pink, White, Vermilion, and Chocolate terraces.

Of the three processes — namely, the stripping of soft strata, the cutting of canyons, and the formation of cliffs — the first and last two are now in a state of great, perhaps maximum, efficiency, while the first is already almost completed. The combined result of the three is a region of strong contrasts, where the three elements — canyons, plains, and cliffs — are utterly different, and yet all in their freshness and nakedness bear the stamp of newness and of a dry climate. But this is not everywhere the case, for in the Colob plateau the ancient mature topography is still preserved, and acts as a foil to set off the new. Yet it is the latter that is impressive. Old slopes have been revived and steepened; enormous tusks of massive red sandstone have been carved out of the once continuous upland (Plate 1 B), and deep canyons marvellously narrow and steep have been sawed far into the depths of the plateau. One of these, that of LeVerkin creek, is so cleft-like that for several miles, where the depth is over fifteen hundred feet, only a narrow strip of sky thirty degrees wide can be seen, and sometimes this is reduced to fifteen degrees. In many places the walls overhang the tumbling brook at a height of several hundred feet, and forever prevent the sun from penetrating to the cool depths, which, after the hot, verdureless glare of the lowland desert, seem ideal in their delightful dampness and abundance of vegetation. Often the bottom of the canyon is so narrow that pine trees, overturned by wind or flood, have not room to fall flat, but lie

against the red sandstone walls, forming bridges under which the trail winds upward along the rough valley floor. Yet, in spite of the depth and impressiveness of the canyons, erosion has accomplished but little since the last upheaval, even although it almost seems that the young canyons are visibly sawing back into the massive stump of the plateau. Their rapid work gives promise of the day when, if erosion continues unchecked, the mature topography must be entirely consumed, and a rugged, inhospitable region will succeed the attractive pasture of the upland of to-day. But that will by no means be the end; for, if the present cycle is allowed to run its course unhindered, a gentler maturity and a subdued old age are still in store for this desert corner and for all the great Southwest.

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EXPLANATION OF PLATES.

PLATE 1.

A. West Temple of the Virgin. Photograph by W. M. Davis. The view looks southeast across the Virgin canyon near Rockville. The broad Shinarump platform is seen in the immediate foreground and across the canyon. Beyond it rises the red sandstone "Temple," cut by deep vertical rifts. Halfway up from the Shinarump platform is the bench of sandstone that caps the Painted Desert shales. Landslide hummocks below this bench show that undermining is actively going on.

B. "Rhinoceros head." Photograph by W. M. Davis. A corner of the red Kanab escarpment, northeast of Toquerville. The view looks southeast from near Dry canyon, toward the extreme southwestern salient of Colob, — a magnificent red sandstone promontory with a tusk-like apex.

PLATE 2.

A. Up Dry canyon. Photograph by W. M. Davis. The view looks east. The cliffs and pinnacles in the distance are red Kanab sandstone. The head of Dry canyon is on the left. On the right rises the cuesta of Painted Desert shales, with its cap of hard sandstone.

B. Anticlinal hill near Leeds. Photograph by W. M. Davis. Looking southwest over the town, one sees the western slope of the cigar-shaped anticlinal nose. On the left the entire Shinarump arch is preserved, but from the centre of the picture southward one sees only the western half of the breached anticline stretching off towards St. George.

PLATE 3.

A. The Hurricane fault-scarp near Toquerville. Photograph by W. M. Davis. Seen from the road to Virgin city, looking north. Here the fault has nearly died out. Against the vertical face of Aubrey limestone on the right can be seen the gently inclined layers of Moencopie shales of the downthrown side.

B. The Hurricane cliff at Virgin canyon. Photograph by W. M. Davis. Looking southeast, one sees the canyon in the centre of the picture. The steep scarp marks the recent faulting along the Hurricane. On the uplifted side is a flat bench of lava over soft Moencopie shales. Just beyond this bench rise

low mature hills of hard Aubrey limestone,—relics of ancient topography along the earlier Hurricane fault line, which acted as a barrier to the basalt when it flowed eastward across the old fault line. In the foreground is a gravel plain covering the lava on the downthrown side of the recent fault. The ruggedness of this fault is shown by the series of "splinters" of lava along the cliff front, just north of the canyon.

PLATE 4.

A. Cliffs near Zion. Photograph by W. M. Davis. Lofty peaks of red Kanab sandstone with white Colob sandstone above.

B. Rock sculpture in Virgin canyon. This view south over Rockville shows something of the characteristic form of each member of the series, from Moencopie to Kanab. In the foreground is the flat-floored valley of the Virgin, with the little Mormon town and its irrigated fields. The bad-land topography of the soft Moencopie shales shows in systematic spurs that run down from the Shinarump platform in the middle of the picture. This platform is banked by landslides of Painted Desert. In the distance is the high cliff front of red Kanab sandstone, showing the characteristic vertical rifts. The bench-maker at the top of the Painted Desert shows distinctly on the left.

PLATE 5.

A. Pleistocene gravels in the Grand wash. The gravel deposit is now being excavated by erosion. The larger boulders are basalt; the smaller are sandstone and limestone.

B. The two faults at Kanarra. The view looks northeast. The new fault forms the prominent escarpment; the old fault passes from x to y, where it cuts the new one. The strata to the left of x are inverted and dip to the northwest; those to the right are normal and dip gently to the east.

PLATE 6.

Cross-sections to accompany map of the Toquerville district. Drawn to scale; no vertical exaggeration.

PLATE 7.

Geological map of the Toquerville district. Topography and geology by E. Huntington and J. W. Goldthwait. The contour interval is 200 feet.

A. WEST TEMPLE OF THE VIRGIN.

PHOTOS BY W. M. DAVIS. HELIOTYPE CO., BOSTON.

B. "RHINOCEROS HEAD."

A. UP DRY CANYON.

PHOTOS BY W. M. DAVIS. HELIOTYPE CO., BOSTON.

B. ANTICLINAL HILL NEAR LEEDS.

A. THE HURRICANE FAULT-SCARP.

PHOTOS BY W. M. DAVIS. HELIOTYPE CO., BOSTON.

B. THE HURRICANE CLIFF AT [illegible]

PHOTOS BY W. M. DAVIS. HELIOTYPE CO., BOSTON.

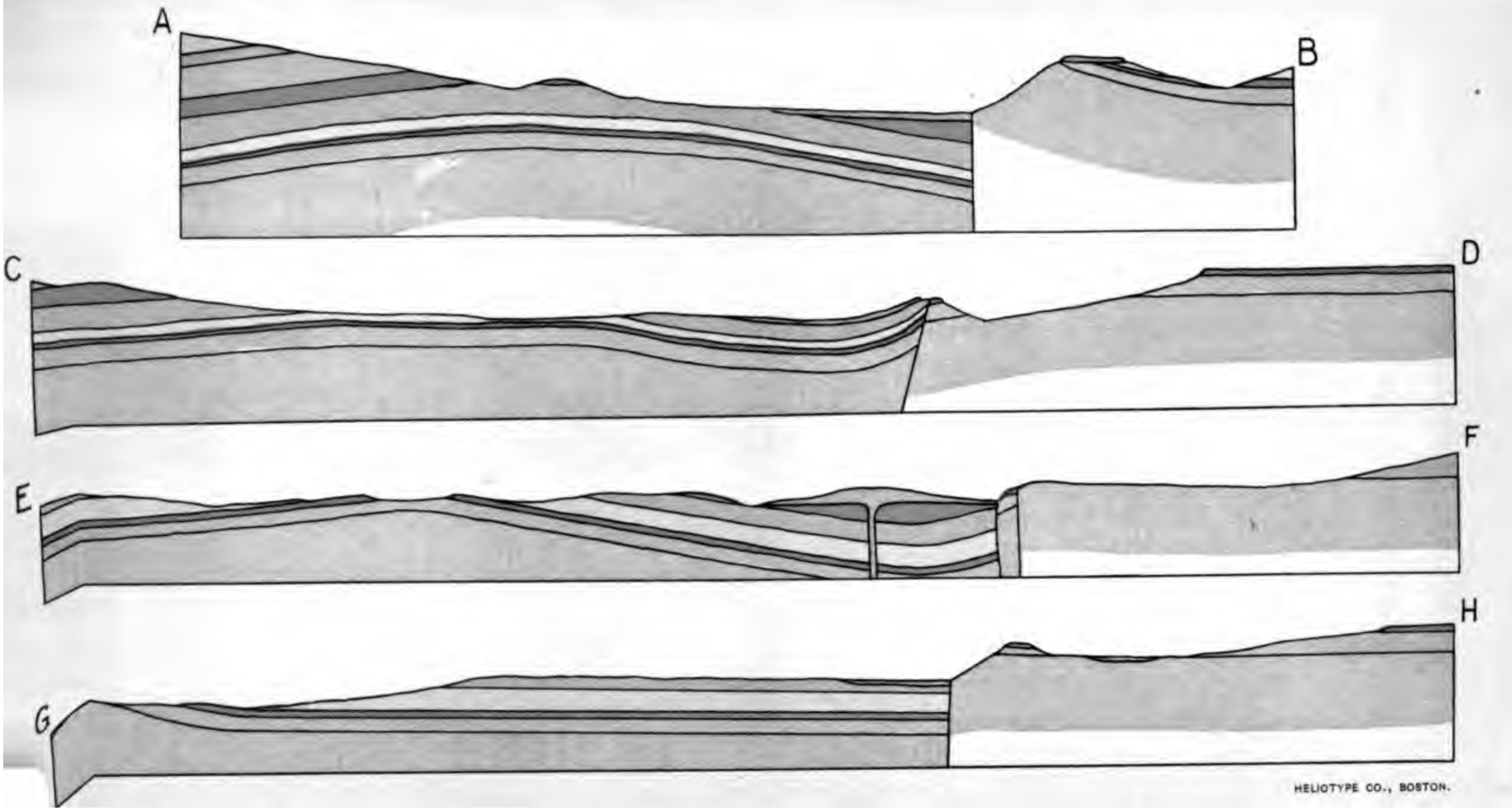
A. CLIFFS OF ZION.

B. VIEW SOUTH OVER ROCKVILLE.

A. PLEISTOCENE GRAVELS.

PHOTOS BY W. M. DAVIS. HELIOTYPE CO., BOSTON

B. THE TWO FAULTS AT KANARRA.



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THE SAND PLAINS OF GLACIAL LAKE SUDBURY.

BY JAMES WALTER GOLDTHWAIT.

WITH FIVE PLATES.

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Introduction.

ALTHOUGH sand plains have received much attention from geologists in New England, it is only of recent years that the grouping of these deltas and their relative altitudes have been studied in a detailed way, with the purpose of tracing the history of the ice-front lakes in which they were built. The work done by Professors Crosby and Grabau, and by Dr. Clapp, has shown the possibilities offered by such a study. During the academic year 1903–1904, as a graduate student under Prof. W. M. Davis of Harvard University, I undertook a study of the sand

plains of the Sudbury valley, twenty miles west of Boston. My purpose was to investigate the grouping of sand plains in a single drainage basin, with greater accuracy in the determination of levels than had hitherto been attempted. The chief result of the work, as will be seen, was the discovery that the sand plains of this district do not conform to the horizontal step scheme of grouping used by Crosby and others for the neighboring extinct lakes Nashua, Charles, and Bouvé; but that they

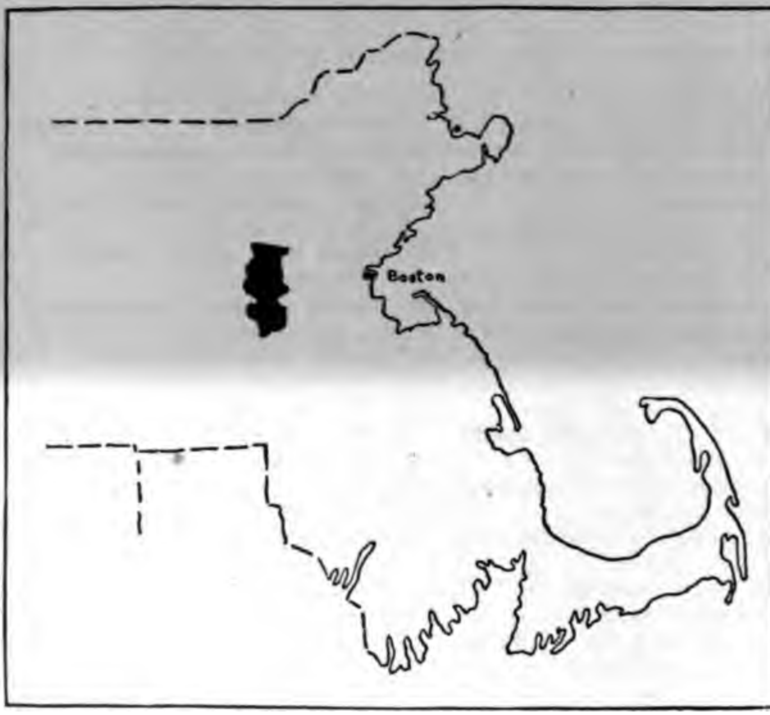

FIGURE 1.
Sketch map of eastern Massachusetts showing location of Lake Sudbury.

seem rather to record a postglacial tilt, by which their original relations of level have been upset.

I shall first review the conditions under which temporary glacial lakes might form, and the probable history they would undergo; passing then to those physiographic features which mark extinct ice-front lakes, especially sand plains, I shall consider the horizontal step scheme of ar-

rangement of deltas used by Professor Crosby and others; and finally, applying this scheme to the data from the Sudbury valley, I shall show that the sand plains of Lake Sudbury do not fall into flat steps, but probably into a tilted step-system.

Conditions of Drainage along the Front of the Retreating Ice-Sheet.

When the ice-sheet melted back over New England, uncovering a land surface of gentle irregularity, the country along its front must have met with temporary conditions of drainage quite unlike those of the present day. The ice must have blocked the courses of many streams, turning them one side or damming them up to form temporary lakes. The melting of the ice itself doubtless contributed in a measure to the volume of the streams in front of it, although the rate of melting may have been so slow that there was only a moderate flooding of the streams.

Where the ice-sheet lay with its front along a divide between two stream systems, or on ground that sloped away from it, there was opportunity in a given time for either an unusual amount of erosion or an unusual amount of deposition. Each stream that drained away from the ice would from the beginning attempt to make an evenly graded bed for itself, either degrading or aggrading according to the conditions of load, volume, and slope: the greater the supply of waste, the stronger the tendency to aggrade; the steeper the slope, the greater the power to erode. An ice-fed stream which was given little waste to carry, and which ran down a steep slope, would be very active in eroding, while another stream which received an abundance of waste gravels, and which ran down a gentle slope, would be active in aggrading. In the first case, the resulting physiographic feature might be a slope or a channel swept clean of all but boulders, coarse gravel, and bed-rock ledges; in the last, it might be an alluvial fan or a waste-filled valley.

As soon as the ice had melted back of a divide, so that its front lay across the lower part of a valley, it enclosed a basin whose margin was in part the ice-wall and in part the high ground which formed the watershed of the valley. Inasmuch as each of these basins was originally covered by the ice-sheet, and was uncovered by its melting off, each must always have contained water up to as high a level as the lowest point on its rim; for each of these low points, or "cols," would have served as an outlet to drain off the excess of water in the adjoining basin. Besides the water derived from the melting ice, whatever water was shed

into the basin by ordinary process of rainfall must have aided in keeping it filled to its capacity.

I propose now to trace the steps which an ice-front lake of this sort might be expected to pass through as the ice retreated.

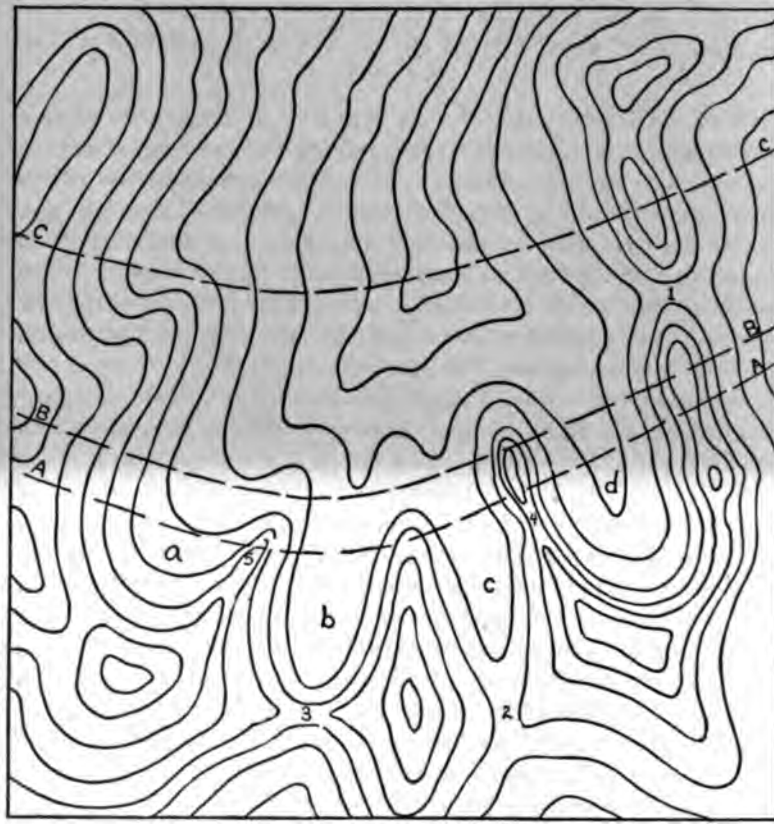

FIGURE 2.

Diagrammatic contour map to show developmental changes in a temporary ice-front lake.

Life History of a Temporary Ice-Front Lake.

When the ice stands just back of a divide, it will form many little lakes at different levels. From the fact that valleys branch and re-branch headwards so that the number of little valleys is greatest near the divide, it follows that the closer the ice-wall is to the divide, the

more little valleys it will shut in, and the more little lakelets there will be. Since also it is probable that the cols at the heads of these little valleys have different altitudes, the lakelets formed at this stage of ice-retreat will not only be many in number, but will have different levels. Thus in the diagram (Fig. 2) the ice standing with its front at A . . A, north of the divide, shuts in four lakelets at different levels, indicated by the figures 2, 3, 4, 5. Lakelets *b* and *c* overflow across the main divide through cols which have altitudes 3 and 2 respectively. It may happen, however, that a lakelet finds its lowest outlet through a col in a secondary divide into an adjacent lakelet or across a secondary divide directly at the ice-front. The latter is notably the case in the temporary ice-front lakes of western New York, described by Fairchild (a, b, c, d, e, f). In the diagram, lakelet *d* drains westward into *c*, through a col 4 in the secondary divide which separates these two lakelets; also, lakelet *a* flows eastward into *b*, across the dividing spur directly at the ice-front, at the level 5. Many small lakelets, then, at different levels, characterize the first stages of withdrawal of the ice from a divide.

As the ice-front melts back, it will retreat beyond the junction of certain of the smaller headwater valleys, so that the separate lakelets originally shut in, in those valleys, will merge into a single lake. Thus, in the figure, when the ice has withdrawn to B . . B, lakelets *b* and *c* will coalesce. As the two lakelets unite, the higher one will drain down to the level of the lower, leaving its old outlet high and dry. At the moment of coalescence, the submerged area will of course be equal to the sum of the two original lakelets; but as the level of the higher one falls, the submerged area is partly reduced in extent, in a measure depending on the amount by which the higher lakelet is lowered, and its shallowness. Thus in the figure, when at stage B . . B lakelets *b* and *c* unite, the level of *b* will fall from 3 to 2, the old outlet at 3 being abandoned, and its shore-line will contract to fit the lower contour. Still, under ordinary conditions, the lake of coalescence will be larger than either of the two original lakelets, for it contains all of one and part of the other. If, however, the outlet of the lake of coalescence is below the level of the bottom of the higher lakelet, it will drain the lakelet dry, and the lake of coalescence will then be no larger than the original lakelet was at the time the two united. In the figure, the total disappearance of a lakelet, due to coalescence with a much lower one, is shown by lakelet *a*, which between stages A . . A and B . . B falls from level 5 to assume the level of the lake of coalescence, which is 3, and later 2, draining dry, however, because the new level 2 is below its lakelet bottom. Early in the with-

drawal of the ice from the divide, then, there is a coalescence of the many original lakelets into a smaller number of larger lakes; some lakelets are wholly drained off. Lakes increase in size, and decrease in number. At the same time, they come more nearly into an agreement of level, the higher levels being abandoned for the lower.

Besides this merging into larger lakes, as the ice retreats from a divide, characteristic of early stages, there soon begins a succession of lowerings of level, brought about by the uncovering of lower cols in the rim of the basin. Each time a lower col is uncovered, a new outlet is formed, and the lake-level falls accordingly. So while the lakes are gaining steadily in area, during the withdrawal of the ice boundary, they are always liable to a loss in area through the lowering of the water-level to fit a new outlet. Thus in the diagram, by the retreat of the ice-front from B . . B to C . . C, the lake gains in area; but since during the retreat a lower col has been uncovered, at level 1, the water-level of the lake has fallen, and there has been a consequent loss in area. In this case, the gain through withdrawal has been greater than the loss by lowering of level. With continued withdrawal, then, there are both gains and losses in area, and successive lowerings of water-level to fit new outlets.

Changes of this sort will go on in the ice-dammed lake until at last the ice abandons the basin and allows the natural drainage to take its place.

Factors which control the Stability of Ice-Front Lakes.

The slower the rate of withdrawal of the ice-front, the longer will the lakes maintain their level and their form; for it is through withdrawal that new outlets are opened and lowerings of level are brought about. The distance from an active col outlet to the next lower one, which will replace it in draining off the water, also controls in part the permanence of form and level of the lake. Again, the strength of material over which the overflow takes place — whether it be till or bed-rock — will affect the permanence of level of the lake, and therefore its form; for if an outlet is actively cutting down its bed, it is lowering the level of the lake which it drains.

The permanence of lake-levels is of great consequence to us, for on it depends the degree of development of all those features which bear record of the lake's history. The longer a water-level is maintained, the greater and the more perfect will be the development of lake-shore forms and deltas, and the more data will be accessible for reconstructing the water-planes which they mark.

Physiographic Features which mark Water-Planes in an Ice-Front Lake.

The features which one may look for as evidence of an extinct ice-front lake are briefly these: —

(*a*) SHORE-LINES, marked by beaches and bars, or by escarpments and benches, built by the waves of the lake wherever the material is non-resistant enough, the exposure great enough, and the level of the lake permanent enough. Benches and bars of this sort are wonderfully well developed along the shores of the great lakes of the ice age, like Bonneville and Agassiz; they are easily traced along the shores of Lakes Chicago, Algonquin, Warren and Iroquois; and they are fairly well shown in New England in the Contocook valley near Hillsboro, N. H.

(*b*) OUTLET CHANNELS, cut across cols or spurs by overflowing waters, wherever the material was weak enough and the outlet was maintained long enough. The remarkable dry gorges of Lake Warren, near Syracuse, N. Y., are fine examples of outlet channels (Fairchild; a, b, c, d, e, f). Another is the valley of the Illinois River, cut by the outlet of Lake Chicago.

(*c*) LAKE BOTTOM DEPOSITS. The finer clays and silts which are fed into the lake will be carried far out, and may settle to form a horizontally stratified deposit. Silt deposits of this nature have been described by Upham in his accounts of glacial Lake Agassiz (d, 20–25).

(*d*) DELTAS. Wherever a stream enters one of these lakes, there is opportunity for a delta to form, provided the supply of waste is too rapid or too coarse for the waves of the lake to wash it away, and provided there is time enough. These deltas are large features in Lake Agassiz (Upham; a, d); and in the New York lakes described by Fairchild fine deltas were built where outlets from one lake entered the next (Fairchild; e, 38, 39, 52, 59).

(*e*) SAND DELTAS, or SAND PLAINS. These are deltas of a special class, and of such importance in New England that they deserve separate treatment. A brief description and discussion of them follows.

Sand Plains—their Form and Structure.

Sand plains are delta-like deposits of sand and gravel, built out from the ice into standing water at its front. The fact that gravels swept out from the melting ice occur thus, in isolated patches, rather than in a vaguely continuous sheet over the whole region, indicates that the

drainage near the edge of the ice-sheet was systematic enough to allow the concentration of waste at occasional favorable points along its front.

In their broader features of form and structure, sand plains resemble deltas built under ordinary conditions, by streams entering a body of standing water. Like normal deltas, they have a nearly flat, gently sloping surface, the "top slope," and an outer or free border, the "front slope," which slants more decidedly and is lobate in form; in composition, the material becomes noticeably finer towards the free border; in structure, the sand plains show inclined beds below with horizontal beds of coarser material above. Yet while sand plains are delta-like in these respects, the peculiar conditions under which they are built give them certain very definite characteristics not common to ordinary deltas. Instead of being fan-shaped deposits built out from lake-shores by single streams, sand plains are more often semi-elliptical in outline, as if built out continuously from the ice for some distance along its front by many streams. In fact, they are most irregular in plan.

The headward border of a sand plain, moreover, is not the lake-shore border of a common delta, but an "ice-contact" or "back slope," which marks the position of the ice-front against which the gravels were laid down. Inasmuch as the back slope shows exactly where the ice-front was when the sand plain was built, it is a great help in determining the ice boundary of the ice-front lake at that time. In linear extent the back slope is straight or irregular, according as the ice-front was straight or irregular. In surface form it may be a simple straight slope of from 30 to 45 degrees, — the natural slope or "angle of repose" assumed by the gravels when their ice support was removed by melting. It is frequently broken, however, by hollows or kettle-holes, where isolated blocks of ice were enclosed in the gravel, and occasionally the ice-margin of a plain is wholly a belt of knobs and kettles, indicating an irregular ice-front where deposition took place among ice-blocks or upon a thin irregular ice-margin. In some cases, also, the ice-border is marked by a high moraine which rises above the surface of the plain, and is bounded on the back by the usual steep ice-contact slope. More typically, however, the back slope meets the top slope of the sand plain at a sharp angle or shoulder. At the back of the plain the material is coarsest, — usually cobbly gravel with boulders, which have reached the ground either by tumbling or melting from the ice.

The top slope is often so flat as to appear like a level plain; but usually there is a perceptible slope, 3 to 5 degrees, from the ice-border towards the free border. Near the back of the plain, kettle-holes are

common, forming depressions in the top slope; near its front the plain is flattest, often unbroken save for shallow depressions which lead down to interlobate hollows, and which seem to indicate partial scouring, subsequent to the building of the plain. Cross-sections through the body of the plain generally show a decrease in size of material towards the front, with also a decrease in thickness of the topset beds.

The front slope, in cases where lobes are well developed, meets the top slope at a low obtuse angle, forming the "brow" of the lobes. This point is important, because it indicates the level of the water in which the delta was built, the flat above the brow being almost wholly of sub-aerial construction and the front slope sub-aqueous. Often, however, the development of lobes is imperfect, or even entirely wanting, on account of the shallowness of the lake, the irregularity of its bottom, or to the building forward of the plain to meet the shore or an ice-border.

Eskers.

Associated with these ice-bound delta deposits are usually ridges of gravel, eskers, which mark the courses of streams that fed the deltas. That these are often subglacial deposits is now recognized by most geologists. They concern our problem chiefly in so far as their position shows an area covered by the ice at the time they were formed, as their general direction indicates the general direction of the ice-front, being naturally perpendicular to it, and as their maximum height shows approximately the maximum height of deltas for the same stage of lake level. For a good description of sand plains and eskers, see Grabau (565–567, 574–578).

Significance of Sand Plains.

In what ways do sand plains, singly and collectively, throw light on the history of the retreat of the ice-sheet?

In the first place, their ice-contact borders give exact locations of the ice-front at the stages they represent. Taking a single sand plain, one can of course reconstruct only a small fragment of ice-front, and can hardly get a fair idea of the whole ice-dam; but by locating and mapping the back slopes of all the sand plains in an extinct lake basin, the fragmentary evidence may be found to fall into so systematic a scheme that it is possible to reconstruct with some accuracy successive lines of ice-front clear across the basin. The alignment of back slopes of two or more neighboring sand plains of the same level is not infrequently so

pronounced that one may fairly assume that the back slopes of these deltas represent portions of the same ice-wall; and when these back slope lines, extended across the basin, connect with morainic patches on its rim, crossing the rim at points that allow an overflow-outlet at the level of the deltas under consideration, the inference of a continuous ice-dam along the line thus traced seems quite safe. If, on the other hand, in going northward one crosses rapidly a succession of deltas whose back slopes extend east and west, the inference is strong that these deltas were not formed at the same time, but successively, as the ice withdrew.

Secondly, the levels of the lobe brows of the sand plains give an accurate measure of the levels of the temporary lakes in which they were built. The lobe brow measures the water-plane for the stage during which the lobe was built. A group of deltas of just the same altitude in a single basin probably belong to a single lake, whose level remained at that height at least so long as these deltas were being formed. The possibility of there having been several neighboring lakelets at identical levels should, however, be recognized and tested by an examination of the topographic conditions and ice-border evidence. If two deltas are at different levels, they probably represent different lakes, or different stages in the same lake, — higher and lower water-planes, — unless there have been post-movements of the land, such as tilting. The question of the arrangement of sand deltas of different levels, and the light that it may shed on the history of a lake, will be considered later (p. 273).

Certain features peculiar to individual sand plains are significant in showing how the ice retreated, its rate of melting, changes in lake-level, etc. That sand plains were built very rapidly — much faster than the ice melted back — is shown, for instance, by the extremely small ratio of backset beds to topset and foreset beds, as first pointed out by Professor Davis (a, 199). Kettle-holes, so commonly marking the places where ice-blocks were enclosed, or even buried in deposits of gravel and sand, have likewise been recognized as evidence that deposition was much faster than ice-melting.

In certain cases, sand plains show a twofold level, having two sets of lobes, a higher and a lower set. These may fairly be taken to indicate a change of level of the waters while the delta was being built. The often observed fact that topset beds truncate the upper parts of foreset beds is believed by Professor Woodworth and others to indicate a change of level, giving a true erosion unconformity.

Importance of Sand Plains in Southern New England.

It may truly be said that sand plains are the most plentiful and the best-developed form of stratified glacial deposits in New England. Their abundance and relative perfection, along with their significance, make them a fitting subject for a study of late glacial history ; at the same time, the relative — one might almost say complete — absence of other records of ice-front lakes in this area, such as wave-cut benches and scoured and aggraded outlet channels, makes sand plains doubly important. It is natural, then, that good work has been devoted to sand plains, and that the progress in the understanding of them has come from eastern Massachusetts.

The first clear presentation of what a sand plain is came from Davis in 1890 (a). Much detailed work is also recorded in papers by Woodworth, Gulliver, and Fuller; and more recently the correlation of sand plains, in order to make out the history of ice-front lakes, has yielded definite results to Crosby, Grabau, and Clapp. Perhaps the most concise example is Grabau's report on glacial Lake Bouvé (b), in which the history of a small ice-front lake in the southern part of the Boston Basin is rather thoroughly treated.

Discordance of Level of Sand Plains.

It is common in eastern Massachusetts to find that the sand plains in a single lake basin vary in altitude. Possibly the lakes were continually suffering changes of level by reason of temporary blocking of their outlets by icebergs or ice-dams, or perhaps as a result of great variation of supply of water from the melting ice. In that case we should expect to find deltas at all sorts of levels. Controlling conditions as irregular as the formation of ice-blockades would involve great irregularity in delta levels.

If, however, there is no such disturbing element in an ice-front lake, one can still see how the deltas in a single lake might vary in level; for if we consider again the normal lake history already outlined, we find that from the natural succession of lower and lower water-planes, as the ice retreats across the basin uncovering lower and lower outlets, there must be lower and lower sets of deltas. Sand plains, then, might mark different levels in the same lake; but in this case the variation would be perfectly systematic. Instead of a promiscuous arrangement of high and low deltas due to irregular blocking of outlets, there would be a definite

grouping of deltas into sets, each set being composed of deltas of a single level or water-plane, and being succeeded by a lower set on the iceward side.

This step arrangement of deltas, in descending groups as one proceeds in the direction of ice retreat, has apparently been recognized by Grabau in his study of Lake Bouvé, and has been applied by Clapp and Crosby to the deltas of Lake Charles, Lake Nashua, and other temporary ice-front lakes of eastern Massachusetts.

The area embracing what Professor Crosby has called glacial Lake Sudbury is the field in which I have attempted to apply one or the other of these two schemes of arrangement of sand plains, — that of confusion of levels or that of horizontal steps.

Glacial Lake Sudbury.

The area occupied by the temporary glacial Lake Sudbury is a belt of lowland on the Framingham sheet (U. S. G. S.), reaching from Lake Cochituate northward to Concord. It constitutes the valley of the lower part of the Sudbury River, which at Concord joins the Assabet to form the Concord River, and as such flows north through Billerica to the Merrimac. The length of the old lake basin, from Framingham to Concord, is about eighteen miles; its average width is about four. That this basin was occupied by a temporary lake as the ice withdrew is well shown by the abundant sand plains which are scattered about in it, and which rise generally to the level of the lowest points on the rim of the basin, near by.

The approximate form and extent of the lake can best be seen on the accompanying map (Plate 5), in which the probable shore-lines are drawn along the contour which lies nearest the level of the adjacent sand deltas. Since these deltas vary nearly 70 feet in elevation, the shore-line follows different contours in different parts of the basin, as will be recognized when the map is compared with the U. S. G. S. contour map.

The country on the western side of the basin is much higher than that which forms the southern and eastern rim, being as a rule well above 200 feet in altitude. The Nashua basin, which lies west of the Assabet and Sudbury, was occupied in late glacial times by a temporary lake whose level was much higher than Lake Sudbury, and which drained eastward into it, as Professor Crosby has shown (b). The waters of Lake Sudbury, then, could not have escaped to the west; they must have reached south and east into the lower basin of the Charles River.

The divide that separates the Sudbury basin from that of the Charles has several gaps which must have been occupied either by outlets of Lake Sudbury or by arms of confluence with the contemporary Lake Charles. Near the southern end of the Sudbury basin in particular, there seems to have been, for a while at least, a confluence of the two lakes; for the present divide is itself made up of sand deltas and associated gravel deposits which appear to carry the water-plane of Lake Charles over into Lake Sudbury. This is seen on the map in the line of sand plains which extend from the big bend of the Charles near South Natick northwest through Morse's, Jenning's, Mud, and Pickerel Ponds to Cochituate. The pass at Morseville, south of Lake Cochituate, where the present divide is still lower (about 145 feet above sea-level), may also have been a point of confluence between Lake Charles and Lake Sudbury.

North of Cochituate, along the eastern rim of the basin, there are only two considerable sags or cols in the divide, — one east of Wayland, near the head of Cherry Brook, and one about a mile south of Lincoln station. Both these passes, however, are above the level of the Cochituate and Morseville passes, and so could hardly have served as outlets for Lake Sudbury unless they were originally lower, and have been subsequently raised by tilting.

Another pass occurs just outside the limits of Lake Sudbury as it is here defined, east of the point of junction of the Assabet and Sudbury (where the Concord River begins), at the head of Hobbs Brook in Lincoln. This is also a relatively high-level pass, about 160–170 feet, judging from the contours. The importance of these higher cols will be shown later.

Arrangement of Sand Plains in Adjoining Districts.

The sand plains of Lake Charles in Wellesley, Needham, and the southern part of Newton, mark a water-plane, the altitude of which is about 150–160 feet. This has been reported and discussed by Crosby and Clapp, who took their levels from the contour maps of the U. S. G. S. Boston and Framingham sheets. The recently revised map of the Boston area has made it possible to get these levels more accurately than before. A table follows which gives the altitudes in the district just mentioned, as they are shown by the newly drawn contours of the Boston map and maps of the Metropolitan Park Commission; also a few altitudes determined much more accurately by a hand-level survey,

and one or two measured approximately by reference to bench-marks of the Metropolitan Water Board along the line of the Cochituate Aqueduct.

Big sand plain at Needham (Boston map, contours) . .	about 160′
Sand plains 1 mile N. W. of Needham " " . .	" 160′
Sand plain at S. end of Waban Lake (Met. W. B. b. m.)	" 150′
Sand plain just E. of Newton Up. Falls " "	" 150′
Sand plain north of Wellesley Hills sta. (B. map)	" 150′
Small sand plain cut by R. R., E. of Waban (hand-level)	" 154′
Big sand plain extending from Newton Centre through Eliot to Waban (lobes 500′ W. of Chestnut St. bridge 518)	" 148′
Sand plain near Woodward and Chestnut Sts. Waban . .	150′
Waban sand plain, E. of Newton Lower Falls (Metrop. Park. Com.)	about 150′

(Hand-level altitudes underlined.)

North of this line of plains, in general north of the Boston and Albany Circuit Railroad, there is a slight drop in the water-plane; for the well-known Newtonville plain has lobes at about 140 feet (by contours on the Boston map), and the little sand plain just northeast of Woodland station, which merges into the higher Waban plain, has lobes east of Washington Street at about the same height, as shown by the 140-foot contour. In general, however, all the plains in this part of the basin of the Charles, south of the Boston and Albany main line, are not far from 150 feet in altitude.

Near the Boston and Albany main line in Auburndale, West Newton, Newtonville, Newton, and Brighton, there is a very pronounced drop in the water-plane, marked by sand plains which lie about 80 feet lower than those just described, viz., at about 60 feet above sea-level. Most of these plains are rather obscured by settlement, e. g. those of Newtonville, Waltham, and Waverley.

There appear to be still lower plains near the Charles River, from the last-mentioned group northward, including one at Nonantum and one south of Commonwealth Avenue near Cottage Farm. The gravel plains of Cambridge and Arlington lie hardly more than 25 feet above sea-level.

This rather sudden drop from the 160–140-foot plains to those of 60 feet and under marks the change from Lake Charles into what Crosby has called Lake Shawmut (130), the smaller successor to Lake Charles, lying wholly within the Boston Basin.

North of Waltham the country east of the Sudbury basin is mostly high ground, nowhere low enough to meet the 60-foot water-plane which would be expected to mark the maximum height of temporary Lake Shawmut there. Naturally, therefore, there are no sand plains in that part of the district, between Lincoln and Lexington. The gravels farther east, in the Mystic River valley, from Arlington to Woburn, lie wholly below 60 feet.

Expectation regarding the Lake Sudbury Water-planes.

The work of Crosby, Grabau, and Clapp, on the temporary lakes of this region, pointed to the likelihood that the sand plains of the Sudbury basin would be found to be arranged according to the horizontal step scheme, i. e. either at a single altitude, marking a single water-plane, or in groups of decreasing altitude from south to north, marking successively lower and lower water-planes.

Clapp recognized from the contour map that the sand plains of both the Sudbury and the Charles basins, since they are over 150 feet, rise above the level of the Cochituate pass (145 feet), the lowest pass in the divide between the two basins; and the two lakes, Sudbury and Charles, must then have had a common level higher than the Cochituate pass, which formed a narrow arm of confluence. The line of sand plains from the Charles at Wellesley northwest to the Sudbury basin at Natick, was mentioned particularly by Clapp as representing an arm of confluence between Lake Charles and Lake Sudbury, during a stage when the water-level was about 160 feet. Clapp speaks of the deltas built in the confluent lakes in these words: —

"The plains at this stage of the confluent lakes [Sudbury, Charles, and Neponset] are by far the best developed of any stage. The broad deposits of Medfield, Millis, and Medway, as well as those in Wellesley, Needham, and West Roxbury were formed at this time. In Newton, they are developed as far north as the Boston and Albany Railroad; . . . West of Needham and Sherborn the plains extend through Wellesley, Natick, and Framingham, across the Cochituate water-parting to the valley of the Sudbury, where an extensive series of the same general elevation is found, extending even down the valley of the Concord River into Bedford and Billerica" (a, 265).

According to this, Clapp recognized the 160-foot level as one that was maintained very long in Lake Sudbury; or, to use his words again: —

"While on the west the ice had retreated as far north as Billerica, it still occupied Boston Bay and a large part of the Boston Basin" (a, 265). (See also Crosby and Grabau, 129).

If his view is correct, the ice-front, just before Lake Charles dropped down to Lake Shawmut, must have extended from near Riverside due north for about fifteen miles to Billerica. Although this extreme irregularity in ice-front is not impossible, one might rather expect that the ice would have melted back from eastern Massachusetts with its front more nearly east and west. In other words, one would naturally look for evidence that at the time the last 160-foot sand plains were formed in Lake Charles in Newton, the ice-front to the west stood somewhere in the Sudbury valley between Framingham and Concord; and that when further melting let Lake Charles down from 160 feet to the 60-foot level of Lake Shawmut, the level of Lake Sudbury fell from 160 feet to the level of the lowest pass on its rim, — the Morseville pass, at about 145 feet. In this case, the sand plains of the Sudbury valley would not mark a single water-plane, but two water-planes, the first at 160 feet the confluent stage, in the southern part of Lake Sudbury, and the second at 145 feet, the stage when Lake Sudbury was tributary to the lower Lake Shawmut by way of the Morseville pass.

From the preceding paragraphs it appears that the levels of sand plains in Lake Sudbury, according to the simple scheme of horizontal steps which Grabau used for Lake Bouvé, Crosby for Lake Nashua, and Clapp for Lake Charles, would show these features: —

(*a*) No sand plains could occur above 160 feet.

(*b*) Either the plains between Framingham and Concord would all mark a level of about 160 feet, or the plains in the southern part would be 160 feet and those in the northern part 145 feet, with possibly double-lobed plains in the zone of change from the higher to the lower level. Concerning the use of the various passes through the divide, as outlets of Lake Sudbury, this would be true: —

(*c*) The Cherry Brook and South Lincoln passes, being above 160 feet (as well as above the more southerly Morseville pass), could never have served as outlets for Lake Sudbury.

(*d*) The Morseville pass alone could have acted as a spill-way, and that only in case Lake Charles fell to Lake Shawmut while the ice-front lay somewhere between Framingham and Concord.

The Horizontal Step Scheme applied to Lake Sudbury.

The four points in the last paragraph may be considered in order:

(a) First, regarding the maximum height of the sand plains. According to the contours of the Framingham sheet, some of the sand plains of the Sudbury valley are above 160 feet. The splendid large delta at North Sudbury, for example, is bordered by a 180-foot contour; the large plain east of Maynard, occupied by the American Powder Company, is shown by a 200-foot contour; and the plains in Concord near Lake Walden and east of the village rise apparently to at least 180 feet. Careful levelling not only confirms the idea that these plains are well above 160 feet, but shows that many other plains which from the map might be taken as 160 feet in elevation are really 10, 15, or 20 feet above that level. A glance at the map (Plate 5) will show this.

(b) The sand plains of Lake Sudbury do not fall even approximately into horizontal water-planes at 160 or 145 feet. The contours, of the U. S. G. S. map, poor as they are, express rather clearly the strong discordance of levels. Taking the contours as truthful only within 20 feet, one finds that the plains do not agree in altitude. One at Wayland, for instance, is bordered by a 140-foot contour, while that at Maynard, about eight miles further north, rises to 200 feet. The real test of accordance, however, comes when careful levelling is done to determine accurately the levels of lobe brows of the sand plains. The figures on the map (Plate 5) show the great range of altitudes that accurate levelling brings to light. Out of sixteen different sets of lobes, measured in this way, only four measure within five feet of 160 feet, and they run all the way from 137 to 201 feet.

(c) Several things point to the probability that the Cherry Brook pass once drained Lake Sudbury. Just west of it in the valley, near Wayland, the level of the sand plains suddenly drops from about 190 feet to about 165 feet, the approximate level of the pass. Along the courses of brooks that head in the pass, as one follows them down-stream, are suggestions of former occupancy by more powerful streams, in the from of boulder-paved stretches, aggraded floors, and pot-holes. The detail of this evidence will be given later. While not at all strong, it is at least suggestive, when taken in connection with the better evidence of water-planes above the level of 160 feet.

(d) The Morseville pass near Steep Rock, and the course of the brook from that point southeast through Little's Pond to the Charles River, show no sign of scouring. The evidences of outlets are in general so

poor in this region, however, that their absence here is of little weight in settling the problem.

The horizontal step scheme, therefore, does not find confirmation in the water-plane evidence in the Sudbury valley. Although this scheme has been thought to explain the grouping of deltas in the adjoining lake basins, it is distinctly the wrong explanation in the case of Lake Sudbury.

Other Possible Explanations.

Whatever theory is true for the grouping of the Lake Sudbury deltas must account for these facts: —

(*a*) The great range of level of the deltas.

(*b*) The large number of high-level deltas, 40–60 feet above the level of the Morseville pass, and 20–40 feet above Clapp's 160-foot "confluent" water-plane.

(*c*) The probable use of Cherry Brook pass as an outlet, although it stands fully twenty feet higher than the Morseville pass at the first-opened end of the basin.

These requirements seem to be met by two[1] theories, — that of irregular fluctuation of lake-level by reason of ice-dams, as already mentioned on page 273, and postglacial tilting of the land in such a way as to throw the levels of an originally horizontal step-system into confusion. Early in the field season my problem was resolved into this, — the collection of data by which I might choose between the two theories, ice-damming or postglacial tilting.

The Ice-Dam Theory.

The condition of delta levels which might be expected as a result of ice-dams or icebergs stranded in the outlets of glacial lakes has already been mentioned. Because blockades might happen at any time, not at regular intervals, the grouping of high and low deltas would be haphazard rather than systematic. By great ice-dams at the outlets the water-level could possibly be raised at times 40–60 feet above the lowest notch in the rim of the basin, so that deltas would be built at that height and higher cols might perform the duty of the one temporarily blocked by ice. One thing should be noted: although lobes might be

[1] A third possible explanation has been proposed by Dr. Clapp in a recent paper on Lake Charles, — viz. a condition of extreme irregularity in the melting ice, involving a network of little lakelets at somewhat discordant levels. This will be considered in a later paragraph.

built high above the level of the lowest col, at a time when the outlet was temporarily blocked by ice and the lake-level raised, never could lobes be built at a level below the level of the col, for the lake-level could not sink lower than that. This point is useful as a test between the ice-dam and tilting hypotheses; for by tilting extraordinarily low lobes may be produced. Haphazard grouping of levels, then, and the absence of lobes lower than the level of the lowest col, are what we should expect from the ice-dam hypothesis.

Tilting in New England presumable from Other Evidence.

Everywhere that glaciated regions have been studied in detail there is evidence of postglacial tilting. DeGeer's work on the raised shore-lines of Scandinavia prove that there, at least, the profound postglacial movements were confined almost perfectly to the area that had been covered by the ice-sheet, as if the earth's crust had sunk beneath the weight of the ice, to rise again when it withdrew (a, 66; b, 25).

In Lake Agassiz, the present slanting attitude of the old shore-lines is believed by Upham to be almost entirely the result of a rise of the land when the ice left it. These tilted shore-lines are exhaustively described and the cause of tilting thoroughly discussed in the monograph on Lake Agassiz (Upham, d). The rate of tilting is usually only about a foot per mile, but towards the northern part of the region it becomes nearly three feet per mile (d, 426, 474–486).

In the Great Lakes region, Taylor has traced the tilted water-planes of the lakes of late glacial times, and has worked out the rate of tilting. In the case of Lake Nipissing, this tilt rate is found to be only about seven inches to the mile; but in other cases it is much higher. The tilting measures most in a direction north 25° east (c, 652).

The work of Gilbert and Spencer on the shore-lines of Lake Iroquois and Lake Warren, the large temporary lakes in the region of Lake Ontario, show that the withdrawal of the ice from that district was accompanied by a very considerable rise of the land, by which the horizontal beaches were tilted into a slanting position. About Lake Ontario the shore-lines of extinct Lake Iroquois are tilted at an average rate of three and a half feet to the mile (Gilbert, 603). In the vicinity of Cape Rutland, north of Syracuse, the rate is about five feet to the mile (Spencer, 128).

In western New York, Fairchild finds that the direction of greatest tilt is between north 17° east and north 20° east (e), indicating "that the isobases of the greater area are curving lines with

convexity southward." In central New York, since the Iroquois beaches in a direction less than three degrees south of east show a tilt rate of only 0.66 feet per mile, the direction of maximum tilt is apparently almost north and south. This suggests that the curve of the isobases continues eastward across New York State, and makes it seem probable that in New England the tilt would be greatest in a direction nearly due north and south, — surely only a few degrees east of north, and quite likely a few degrees west of north.

DeGeer's summary of the evidence of postglacial tilting in New England, in the form of raised marine beaches, benches, and sea-floor sediments between Massachusetts and the Provinces, is the most comprehensive and reliable study yet published. Incomplete as the evidence is, one cannot deny that there has been a postglacial uplift of the north with respect to the south. The discovery of further details, like that by

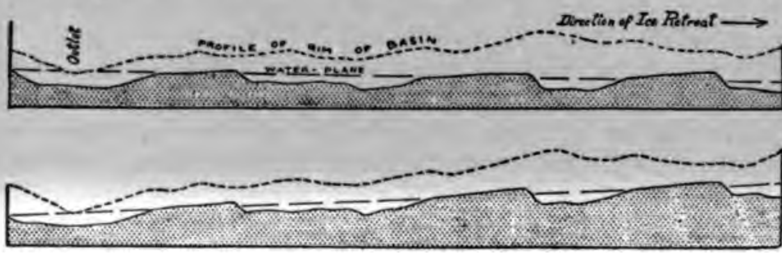

FIGURE 8.

Diagrams showing how postglacial tilting produces a discordance of altitudes among sand deltas.

In the upper figure, three deltas stand at the same altitude, marking a horizontal water-plane which is controlled by the height of an outlet at the further end of the lake. In the lower figure this region has been tilted, so that the three deltas stand at different altitudes, marking a slanting water-plane. The deltas now stand higher than the outlet col.

Tarr and Woodworth of the beaches at Cape Ann (Tarr), will doubtless some day furnish the data for determining with more accuracy the true rate of tilt along the coast and the direction of the greatest slant. In the mean time, can we not gather valuable evidence of tilting by studying the water-planes of temporary ice-front lakes like the Sudbury, Nashua, and Charles?

To sum up: From the work of Taylor, Gilbert, Fairchild, and DeGeer, we might reasonably expect that whatever evidence came to light would show a tilt towards the south of a few feet to the mile, with its greatest slant in a direction about due north and south (considerably west of the N. 17° E. line of central New York).

The Probable Effects of Tilting on Temporary Lake Features.

Taking the typical temporary lake, with its successively lower outlets and sand plains in the direction of ice-retreat, let us see how tilting will rearrange the levels.

To take the simplest case, — suppose that a single water-plane, marked originally by a set of sand deltas with brows at a common level and an outlet at a level slightly below them, is tilted evenly, with a relative elevation of the iceward side (see Fig. 3). After this movement, just as before, all the brows of the sand deltas lie in a single water-plane; but the plane is no longer horizontal, — it slants away from the ice. The sand deltas nearest the ice-field have been lifted higher than those farthest from it, the brows of the two deltas at these two extremities of the lake measuring the greatest difference of elevation of the inclined water-

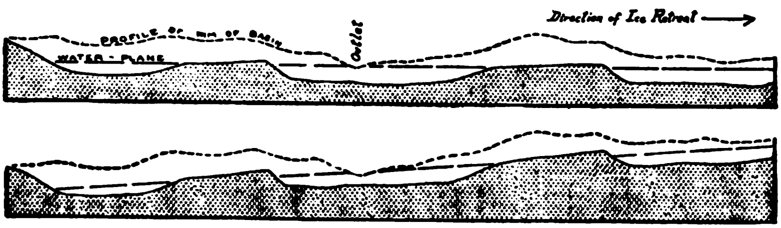

Figure 4.

Diagram showing how postglacial tilting, under certain conditions, may place a delta below the level of the corresponding outlet col. In the upper diagram, the ice-sheet has melted back more rapidly along the rim of the basin than in the basin itself; consequently the first delta built — the one on the left — belongs to an outlet col on the iceward side. With further retreat, a second delta has been built, on the right. In the lower diagram, the region has been tilted; and the first-formed delta has thus been brought below the level of the outlet.

plane, and the deltas intermediate in position showing intermediate elevations of a measure proportionate to their distances from the two extremities. The outlet associated with these deltas, originally at or somewhat below the horizontal water-plane, will of course now be found at or a little below the slanting water-plane, as shown in Figure 3. If its position is at the further extremity of the lake (relative to the ice), or if it is at the further end of the water-plane for its stage, its level will be the lowest point marked on the water-plane; but in case the outlet was on the side of the lake, and icewards from the first delta built at that water-plane (a condition of things made possible by an irregular ice-front), its actual altitude measured after tilting will be higher than that of the sand delta whose level it once controlled (see Fig. 4).

Since in the lakes of eastern Massachusetts there is not usually a single water-plane, but several, it is worth while to consider how a set of these will look when tilted. In their original position, as we have seen, the deltas occur in groups, each group marking a horizontal water-plane, and standing higher than the group that lies icewards from it. Between the brow of any sand delta of the higher group and that of any delta of the lower group, there is a difference of elevation equal to the difference of the lake-level in the two stages. The outlet for each water-plane has its position just below the lobe-brow levels, and is likely to occur at or near the outer extremity of the water-plane. Now, if the region be tilted, each water-plane is tilted as already discussed, and the brows of the plains in each group will therefore indicate a rising of the water-plane icewards. The original drop from one water-plane to the next can no longer be measured by the difference in altitude between the lobe brows of any two representative deltas, for the original difference of elevation between them has been modified by the tilt. It may be that some of the deltas of the earlier, higher water-plane now stand actually lower than some of the deltas of the later, lower water-plane. The sand deltas, then, after tilting, should ascend icewards, but with a drop in elevation at each new water-plane. The relation of the altitudes of outlets would likewise be disturbed. Take, for example, any two adjacent outlets controlling the water-planes of two neighboring groups. Before tilting, the iceward outlet is the lower. The effect of tilting is to raise the lower outlet toward, to, or even above the level of its neighbor. The relative altitude of the two after tilting will depend on (*a*), the original difference of altitude (*b*), the distance apart of the outlets, measured in the direction of the tilt, and (*c*), the rate of tilting.

If the tilting of the extinct lakes was a simple uniform one, taking place after all the deltas had been built, the tilted water-planes should of course all have the same slant; in other words, the water-planes should in that case be parallel. But if the tilting was already going on during the retreat of the ice and the building of the deltas, the older water-planes at the further end of the lake would have been tilted more than the younger water-planes. Diagrammatically, the two cases would appear like Figure 5. Gilbert speaks of the application of this principle to the lakes of the Ontario basin (603).

In summing up the condition of lobe brow and outlet levels for a lake which has gone through the normal ice-front history, plus postglacial tilting, this may be said: the sand plains should be resolvable into

groups, each group being composed of deltas whose lobe brows fall into a single tilted water-plane. In each group one should find, as he proceeds icewards, a steady increase of altitude of the brows, until he reaches a new water-plane in the vicinity of a lower outlet, where a sudden drop of altitude to the lower water-plane would be followed by a new group of ascending deltas. Such an arrangement may conveniently be called a slanting step-system.

Methods and Results of Levelling in Lake Sudbury.

To determine whether the Lake Sudbury deltas lie in a slanting step-system or only in haphazard fashion, a good deal of detailed levelling was necessary. Through the kindness of the Division Engineers of the

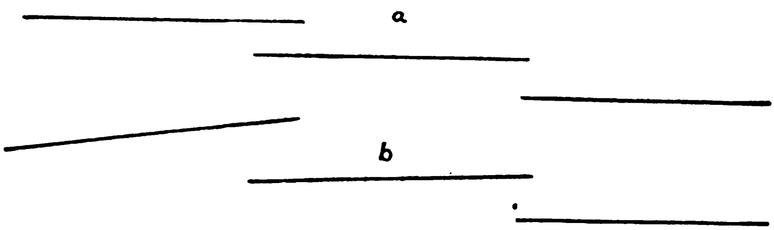

FIGURE 5.

Effect of tilting a step-system of three horizontal water-planes, (a) after the ice has withdrawn from the region, or (b) while the ice is retreating across the region. In the latter case, the water-plane which is first abandoned is tilted more steeply than its successors.

various railroads and of the Engineers of the Metropolitan Water Board, I secured bench-marks which in almost every case I could conveniently use as a base, — such as the top of the rail at a certain bridge, road-crossing, or turnout, or the capstone of a culvert along an aqueduct line. From such a starting-point, with a rodman, I ran levels over a circuit as short as possible, ranging from a few hundred feet to three miles, using in some cases a surveyor's spirit-level, but more often a Locke hand-level, which proved to be a much more rapid means of levelling, and nearly as accurate. The probable error by this method was not over one or two feet per mile. On the map (Plate 5) all of these accurately determined levels and the lobe brows from which the average height has been computed are shown in black figures, while other altitudes determined by aneroid or rough computation are shown in parenthesis. These last-mentioned levels involve an error of from 5 to 20 feet. All altitudes are referred to mean low water, Boston City base.

A study of the map will bring out the following facts as to the general arrangement of deltas.

In the southern part of the basin, about Lake Cochituate, the sand plains lie at about 170–180 feet, i. e., the highest lobes mark a water-plane at that altitude; but in more than one case there are lobes at different altitudes on a single sand plain, as if marking changes of level during the construction of the delta. This is remarkably true of the big sand plain just east of Saxonville, which has at least four different sets of lobes.

The two sand plains north of the last, which are cut by the Sudbury Aqueduct, and the plains northwest of them in Sudbury, are higher, — about 190 feet — although these also have one or two lower sets of lobes.

Going on towards Wayland, one finds there a sudden drop in altitude of the sand plains down to about 160 feet, represented by the three plains near Wayland station. The plain cut by the Massachusetts Central Railroad west of the Sudbury River stands at an intermediate height, however, 175 feet.

From Wayland northward through Lincoln to Concord there is a steady increase in height of the sand plains, — 160 feet at Wayland, 175 feet at South Lincoln, and 195 feet at Lake Walden. Across the river on the west side of the valley, the plains show the same sort of an increase in height going north, through 175 feet near Sudbury Centre to nearly 200 feet around North Sudbury, Maynard, and Concord Junction. Right at the north end of the Sudbury basin, where the Concord valley begins, there is a second pronounced drop in level of the sand plains from 200 feet to about 150 feet. The high plateau east of Concord village is the farthest north of the 200 feet group of deltas. Beyond that, the gravels occur only at lower levels.

In general, then, the discordance is not haphazard, as it would be if it depended on the ice-blockade theory. It is quite systematic; the plains rise from Cochituate north to Wayland, drop down there from about 190 to 160 feet, then rise steadily from 160 to 200 feet at Concord, where there is a second drop. There is a strong suggestion, in short, of a slanting step-system.

Water-Planes slanting southward, Seven Feet per Mile.

The first three sand plains to be measured with a hand-level were the Lake Walden plain (194 feet) and the two deltas east of Wayland, — one

south of the railroad (161 feet), and one north (163 feet). The two deltas at South Lincoln, halfway between the Wayland plain and the Walden plain, had been found by aneroid readings to be of intermediate altitude, somewhere between 170 and 190 feet. Plotting the three accurately measured plains in cross-section, I found that they fell into a single straight line. Then, on the assumption that all the plains between Wayland and Concord had originally stood in the same horizontal plane, and that this plane had since been tilted up on the north, I plotted the position of the two South Lincoln plains, and found that in order to lie on this tilted water-plane the southern one should have lobes at 177 feet and the northern one at 180 feet. Hand-level surveys, made a few days later, fulfilled the prediction; for four lobes measured on the south plain averaged 179 feet, and three on the north plain stood at about 182 feet. Inasmuch as the circuit for this levelling, from Lincoln station to the plains and back, was a very long one — three miles — involving a probable error of three feet, the results in this case were fully as satisfactory as could have been expected. The water-plane thus determined slants southward at the rate of about seven feet per mile.

Having thus gained faith in the tilting hypothesis from the element of fulfilled prediction in levelling, I continued to collect data, and found that in nearly every case the measurements of lobes fell on slanting water-planes which passed through one or the other of the passes in the rim of the basin. The final result of this grouping of deltas is shown in Plate 4, where all of the measured lobes are plotted to scale along a north-south line, and the slanting water-planes drawn through them. It will be seen that the Cherry Brook water-plane is determined by lobes measured on nine separate deltas. Between Wayland and Concord Junction all the deltas measured, except two, lie close to this single water-plane, as does also the Cherry Brook pass itself. The other water-planes are not so well determined; but they explain all the features save a few which will be discussed later.

On the basis of the Cherry Brook plane, then, there seem to be five parallel water-planes marked by the lobes of deltas in Lake Sudbury: —

(*a*) The water-plane of confluence between Lakes Charles and Sudbury, ranging from 150 to 191 feet (sand plain at Waban Lake to two plains cut by the Sudbury Aqueduct south of Wayland). (*b*) The Morseville water-plane, marking the stage when Lake Sudbury drained down into Lake Shawmut through the Morseville pass. This stage is shown by lobes of the plains about Saxonville and Wayland. (*c*) The Weston water-plane, marking a stage of short duration, brought about by the uncovering of

part of the Cherry Brook pass before the lowest part of the pass was free of ice. The lobes that seem to mark this range from 164 to 175 feet. (*d*) The Cherry Brook water-plane, which is marked by nearly all the deltas between Wayland and Concord, ranging from 160 to 200 feet. (*e*) The Hobbs Brook water-plane, marked by the lower deltas of Concord, with lobes in the vicinity of 150 feet.

Recognizing that a grouping into seven-feet-per-mile water-planes may be incorrect, for reasons which will be brought out later, let us nevertheless trace the probable history of Lake Sudbury on the basis of a postglacial tilt of seven feet per mile towards the south. For this purpose the groups of the system of slanting steps may be considered in order of their age.

Probable History of Lake Sudbury.

THE STAGE OF CONFLUENCE. — The stage of confluent lakes which saw the birth of Lake Sudbury seems to be marked by deltas which occupy the southern part of the Sudbury basin as far north as the Sudbury Aqueduct south of Wayland. They apparently form a continuous belt from the Charles River, near Lake Waban, northwest across the divide to the Sudbury basin at Cochituate village. They also occur on the divide just south of Natick. Their distribution in the two basins in such a way as to actually form the present water-parting at Natick and Cochituate, together with the fact that the deltas are considerably higher than the Morseville pass, point to a state of confluence between the two lakes while the ice in the Charles valley was retreating towards the present position of the Boston and Albany Railroad and its front in the Sudbury valley was receding towards Wayland.

The levels of most of the plains of this stage have been determined only approximately. It has been hard to secure convenient bench-marks from which to measure some of them; consequently aneroid readings and map contours have been relied on for levels. Moreover, the plains in the southwestern corner of the basin, around South Framingham and southwest of Lake Cochituate, have not been mapped.

THE MORSEVILLE STAGE. — The drop from Lake Charles to Lake Shawmut, when the ice had withdrawn to the position of the Boston and Albany Railroad, must have caused a simultaneous drop in Lake Sudbury from the confluent level down to the level of the Morseville pass. The lowering of level seems to have come when the ice-front in the Sudbury basin was near Wayland, and while the deltas at the Sud-

bury Aqueduct were being built; for these have lobes at two levels which apparently fall into a water-plane with the Morseville pass and with a set of lobes on the Saxonville delta west of Lake Cochituate.

The Saxonville plain deserves special mention, for it has lobes at several distinctly different levels. On the northwest side, where these lobes are best seen, the plain has clearly been built outward towards the northwest from an ice-front at the northern end of Lake Cochituate. The occurrence of lobes in increasingly lower and lower sets on this single plain indicates that the water-level fell while the delta was being built, possibly in successive stages. The way these lobes fall on the probable water-planes of Lake Sudbury is seen in Plate 4. Those of the highest set, at about 185 feet, are irregular, and have been measured only approximately. They seem to represent the stage of confluence. Below them, at the northwest corner of the plain, are two or three well-formed lobes, at 161–165 feet, which have a peculiar and very striking surface of cobblestones, as if all the finer sand had been washed down from them after the water-level fell. These lobes seem to fall on the Weston water-plane (the next one to be considered). Between two of them a lower lobe (at 149 feet) has been built; and this falls on the Cherry Brook water-plane. Lowest of all is a terrace with several fine lobes, at 137 feet, which have a remarkably sandy composition. On the south side of the plain, southeast of Saxonville, lobes occur at 167–172 feet, and a lower set at 152 feet. The 167-foot level, marked by at least two lobes, falls on the Morseville water-plane. The 172-foot lobe probably represents the time when the waters were just falling to the level of the Morseville pass, or when the pass was first occupied by an outlet which cut down five feet before the 167-foot lobes were formed. In all cases, the higher lobes lead down to the lower lobes by smooth slopes. It seems probable, when these lobes are identified with the various water-planes, that the Saxonville sand plain was being built forward from a large ice-block in Lake Cochituate when the main part of the ice had retreated northward beyond Wayland, and perhaps even as far as Concord.

THE WESTON STAGE. — While Lake Sudbury stood at a level controlled by the Morseville pass, the ice-front receded from the Aqueduct plains towards the present position of the Massachusetts Central Railroad. On reaching this position it must have uncovered the pass in the Sudbury-Charles divide that is occupied by the railroad. Although this pass now stands higher than the Morseville pass (over 160 feet, whereas the Morseville pass is 145 feet), its greater height seems to be due to

eing built; for these have lobes at two levels to a water-plane with the Morseville pass and the Saxonville delta west of Lake Cochituate.

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postglacial tilting, judging from the slant of the water-planes as marked by the lobes of deltas. As already mentioned, also, there is a pronounced drop in altitude of deltas just west of the pass in Wayland, from 190 feet to about 160 feet, the general altitude of the pass.

Before the lowest part of the pass (north of the railroad, near the head of Cherry Brook) was opened, there was of course in all probability a partial evacuation of it, along the northern slope of the high ground south of Weston village. The well-formed sand plain cut by the railroad just east of East Sudbury station has lobes at 175 feet which may very likely have been built at this time. There are lobes also on both the north and south sides of the Saxonville delta, which fall into a tilted water-plane with this 175-foot delta. That there are so few deltas marking this stage is natural enough, because it is essentially a temporary stage which was soon followed by renewed lowering of water-level as the ice withdrew so as to allow the water to pass eastward by lower paths, — first by the little forked brook half a mile northwest of Weston station, and later by Cherry Brook. These two probable lines of escape are so nearly at a common level that there has been no attempt made to differentiate two water-planes for them.

THE CHERRY BROOK STAGE. — The deltas built while the Cherry Brook pass was a spill-way mark by far the best-determined water-plane. Lake Sudbury seems to have been maintained at this height from the time the Wayland deltas were formed until the ice-front had withdrawn eight miles to Concord; for between Wayland and Concord the lobe altitudes of nearly all the deltas lie on a single slanting water-plane. The cross-section (Plate 4) shows how closely eight of these deltas fall on the water-plane. It is also remarkable that if the water-plane be extended south from Wayland it just hits the 149-foot lobe of the Saxonville delta. This seems to show that the Saxonville delta was still being built out from the Lake Cochituate ice-block when the Cherry Brook pass was opened.

The two large plains in North Sudbury seem to be the only deltas in the northern part of the basin whose lobes do not lie on the tilted Cherry Brook water-plane. Since there is no reason to doubt the accuracy of measurement of their altitudes, they are thus far unexplained. The splendid big delta west of the railroad has lobes at 201 feet (14 to 20 feet too high for the water-plane); the delta east of the railroad has lobes at 193 feet (6 feet too high).

THE HOBBS BROOK STAGE. — It is possible that the pass at South Lincoln became an outlet to Lake Sudbury when the ice had retreated

that far; but there is no evidence of it in slightly lower lobes or in signs of scouring along the courses of the brooks that head in the pass. The height of the pass, moreover, is very nearly as great as the computed height of the Cherry Brook water-plane. Consequently it seems reasonable to suppose that not until the ice had melted back beyond Lake Walden, so as to uncover a pass at the head of Hobbs Brook, three miles to the east of Concord, did Lake Sudbury suffer a marked lowering of level. With the opening of the Hobbs Brook pass, the water seems to have fallen about 50 feet, judging by the height of the lower deltas at Concord and Concord Junction. Since this new water-plane, 50 feet below the other, begins where the Concord River begins, it would perhaps be appropriate to consider the opening of the Hobbs Brook pass as marking the death of Lake Sudbury and the birth of a new lake, Lake Concord. That the transition was not immediate is shown by lobes of intermediate altitudes on the sand plains near Concord Junction.

Outlets of Lake Sudbury.

In several papers on the temporary glacial lakes of central New York, Fairchild describes a large number of well-developed outlet channels. Next to delta deposits, these channels are the clearest records of the extinct lakes of this region; and they are certainly the most striking of all. They are described as often heading in low marshy ground on a water-parting, called a "swamp col" by Fairchild (e, 36, 37, 38, 58, 61). As channels with definite walls, they run often nearly straight for a mile or so. One which drained Naples Lake, given as a good example of an abandoned river-bed, is described as "over a mile long, 20 to 25 rods wide, with banks 15 to 25 feet high, and a flood plain of varying width," and a "pavement of cobbles and boulders in the bottom of the channel," which "is still well shown through the vegetal accumulation" (a, 362). When, as in this case, the channel is cut in drift, the banks and flood plain seem to be well developed. Not infrequently, however, a channel has rock walls and a swampy bottom. Some of the old outlets of Genesee Lake are rock gorges with swamps partly occupying the channel floors (c, 434, 435, 436, 437, 438). In certain cases, deltas built into these channels from side ravines have levels of from 70 to 80 feet above the channel floor, seeming to indicate a down-cutting of the floor 60 to 70 feet since the channel first opened (c, 435). Other outlets of Genesee Lake are broad, with flood plains. At the lower ends of these channels are commonly plains or deltas of detritus, built out by the stream which

cut the channel above (e, 38, 52, 54). One at Cedarville is more than a square mile in area. Most striking of all are the deep rock gorges at Syracuse, which mark outlets of glacial Lake Warren. One of these is two miles long, 8,000 to 10,000 feet wide at the bottom, and 125 to 150 feet deep, with nearly vertical walls; another is a limestone gorge, with a cataract cliff 160 feet high, at the foot of which is a deeply excavated pool (e, 60).

In New England, the outlets of temporary lakes are not nearly so well defined. In the case of Lake Nashua, Crosby has discovered what he considers to be evidence of outlet scouring in the pass at Clinton, — a sag in the divide, which must have been used as a spill-way, judging from the height of sand plains in the Nashua valley near by. Professor Crosby says: "This is an ideal outlet — narrow, well-defined, and with every indication of a strong stream flowing swiftly down around Snake Hill into the valley of North Brook. In the lower part of its course, especially, this stream washed away all the fine parts of the till, and its path is now strewn with thousands of residuary boulders. That this is the work of a long-continued torrent, and not of some transitory cloud-burst, is proved by the pot-holes to be seen in the bed at North Brook at West Berlin, in situations which make it well-nigh impossible that they can have been formed by the modern brook" (a, 318).

Similar traces of spill-ways are to be seen in some of the cols in the eastern rim of Lake Sudbury, and along the courses of the brooks that head in them. A half-mile northwest of Weston station, the contours show a forked pass at about 160 feet, occupied by the headwaters of a brook and crossed by a road that runs north from the village. According to the contours, this col is the lowest northeast of the Saxonville pass, being probably 10 feet lower than the one south of Weston village. It is therefore a place which deserves critical examination for evidence of outlet scouring.

Going north along the road from the railroad west of Weston station, one crosses the western end of a ridge of bed rock with a thin till covering. Reaching the southern fork of the brook, one finds west of the road a broad swampy area, well wooded and almost flat, at an elevation of 163 feet (aneroid). Beginning directly at the road and extending east along the line of the brook, is a pavement of boulders so thick as to be remarkable even to one not looking for features of the sort. The paved zone is about 100 feet wide, and consists of boulders of moderate size, as well as a few cobbles. It follows the lowest ground along the brook, which is about 3 feet wide. About 300 feet east of the road, the

pavement rather suddenly stops, and the course of the brook is through a narrow grassy flat, which soon broadens out into a broad swamp at the junction of the two headwater forks. The absence of boulders and blocks along the brook just up-stream may be largely or wholly due to the construction of a private road across the brook about 300 feet east of the highway, — the rocks having been collected for its construction. Where the northern of these two brooklets crosses the road, one finds on the west side of the road, going up-stream, a few bare ledges and many blocks, including some large boulders, and beyond these the flat swampy ground already mentioned as the source of the brooklets. The elevation at the road at this point is 165 feet (aneroid). Going down-stream from the road, one finds a pretty continuous boulder pavement as far as the broad meadow at the junction of the two brooklets, though the boulders are much thicker in some places than in others. There are a few bare ledges here, also.

On both these brooklets the boulder pavement is a distinct and striking feature. There is no such abundance of blocks on the slopes which lead away from the brooks to the north and south. The distribution is emphatically along the two lines of lowest ground; and the width of the pavement together with the general good size of the boulders seems to indicate that scouring much stronger than that of the present little stream has gone on in the past, washing the finer parts of the thin till cover down-stream, and leaving bare ledges and a thick pavement of boulders. There are no steep banks, however, enclosing the paved zone, such as one might expect to find.

Down-stream from the junction, the brook follows generally a rather broad flat meadow; and though boulders may once have been plentiful at certain points along its course, there is no longer anything like the boulder pavement seen up-stream. From the railroad for about 500 feet southward along the brook, however, there are a good many boulders, possibly of some significance. Below this the valley becomes extremely broad, flat, and swampy. These flat meadows along the brook are evidently aggraded parts of its valley; and they may have been built up by the supply of gravels and fine material from the scoured boulder-paved pass up-stream.

Along the course of Stony Brook, in several places, particularly between Kendal Green and Roberts, there are stretches of boulder pavement similar to those just described. Doubtless the brook gets its name from this fact. Moreover, the two large pot-holes beside the railroad embankment, near the northern end of Stony Brook Reservoir, may

have been formed by the action of a powerful stream that was the outlet for Lake Sudbury. Whatever water spilled over at Weston, down Cherry Brook, at South Lincoln, or at the head of Hobbs Brook, would have run into Stony Brook; and marks of scouring, such as boulder pavements and pot-holes, should be expected wherever the course of the stream was down a steep slope.

Heading on the southeast side of the Hobbs Brook pass, Hobbs Brook flows south into Stony Brook, a large part of its course having been dammed up to form the Cambridge Reservoir. On the northwest side of this reservoir, about a mile north of Prospectville, near where the parkway joins Concord Avenue, is a small exposure of bare rock, rounded and hummocky, as if worn by a powerful stream. About a quarter of a mile below the reservoir, along the course of the brook, is a pavement of boulders about 100 feet wide and 300 feet long, — again suggesting the former occupancy of the course of Hobbs Brook by a powerful stream at a time when the pass above it served as a spill-way.

Similar evidences might be expected below the Morseville pass, in the brook that drains Little's Pond, but I have looked in vain for them. The brook that heads in Weston village shows no sign of scouring. Just where its course begins to be steep, a millpond has been formed, and the aspect of the ground is otherwise changed by artificial grading. Cherry Brook exhibits no boulder pavement.

Direction and Rate of Tilt is questionable.

Judging from the fact that 8 of the 11 accurately levelled deltas between Wayland and Concord fall nearly in line for a single water-plane when plotted with respect to a north-south line, as in Plate 4, and that they do not harmonize so closely when plotted with respect to any other direction, it seems safe to say that the direction of maximum tilt is somewhere about due north and south. The rate of tilt measured along this slanting water-plane of the Cherry Brook stage is a little over 7 feet per mile, steeper than what might be expected from the evidence of Gilbert, Fairchild, and DeGeer. The other water-planes all lie parallel to this well-defined Cherry Brook plane, — that is to say, the same tilt is recorded by all.

Over against the striking conformity of delta levels to the 7-feet-per-mile water-planes, there are a few details which suggest that the tilt is even steeper and the grouping consequently somewhat different from that just given.

Two fairly well developed deltas at North Sudbury which should fall on the Cherry Brook water-plane if the other deltas are correctly grouped, stand 6 and 14 feet too high, respectively. These were carefully levelled, and there is no reason to doubt their altitudes, 193 feet and 201 feet. Ice-damming might account for this, or it is possible that the deltas were built in a little high-level lakelet held in by an irregular ice-front against the western side of the valley, but there is nothing to support these explanations save the necessity for them. Tilting could explain the extraordinary height just as well, — but not tilting at the rate of 7 feet per mile.

The extraordinarily low lobes on the northern side of the big Saxonville delta, at 137 feet, have already been spoken of; but their altitude has not yet been explained. These five or six lobes are unusually well formed, and compel attention. On seeing them, my first idea was that they belonged to the Cherry Brook water-plane; but that plane, if extended southward from Wayland with the 7-feet-per-mile slant, hits the Saxonville delta at 149 feet, where there is one lobe, to be sure, but only one, and to all appearances a lobe that registers simply the transition from one long-lived water-plane, here 163 feet, to another permanent water-plane at 137 feet.

Curiously enough, the "too low" lobes of Saxonville and the "too high" 201-foot delta of North Sudbury can be brought by plotting into a single slanting water-plane which passes through the two Wayland deltas and just above the Cherry Brook pass, as shown in Plate 3. The Cherry Brook water-plane thus drawn has a slant of over 11 feet per mile. The deltas in Lincoln and Concord falling below this steeply inclined water-plane might perhaps owe their level to an outlet through the South Lincoln pass.

Drawing other 11-foot-per-mile planes for the higher Saxonville lobes, one gets some curious surprises in the way in which lobes fall on single water-planes; but the difficulties in explaining the occurrence of these water-planes are so great, and the slant of them is so extraordinarily steep, that little faith can be placed in them.

Plotting the delta levels with respect to an axis in any other direction seems to bring no better results. Further detailed work is needed, if they are all to be brought into perfect harmony with a single slanting step-system.

While the 137-foot lobes are so troublesome, in being too low for their water-plane, they have a peculiar value. Their altitude is a little below that of the very lowest col in the divide, — the Morseville pass, — which,

judging from data secured from the Metropolitan Water Board, must be over 140 feet. As mentioned on page 281, this condition of things seems to be explainable only by tilting.

The Theory of Many Lakelets.

In a recent paper on the sand plains of glacial Lake Charles, Clapp states his belief that the ice melted off from eastern Massachusetts in an extremely irregular fashion, so as to form a network of marginal lakelets, in which, here and there, the deltas were built. This theory seems to account for the prevalent discordance of altitude in neighboring deltas; and it is based on observations which Clapp sums up under four heads (c, 207). In reviewing these features in order, let us consider whether they are to be seen in Lake Sudbury or not.

(1) The plains in the northern part of Lake Charles, according to Clapp, are distinctly marginal in their position, — grouped about the shores and islands of the extinct lake, as if they had been built not in an open water body but in single lakelets which formed along the sides of the basins while the ice still occupied the central portions. This marginal distribution of sand plains is not distinctly the rule in Lake Sudbury. Most of the large deltas are not far from the rim of the basin; but since there was shallower water near the rim, it is natural that there the deltas were most quickly built and thus grew to largest size.

(2) Clapp remarks that in several cases the ice-contact slope extends clear around the sand plain, except on that side where there is higher ground. In some cases there is an approach to this in Lake Sudbury — e. g. the large Wayland plain, the Walden plain, and the sand plain which lies a mile due west from South Lincoln station; but as a rule about half the border of a delta in ice-contact and the rest is either definitely lobate or flattish, as where there was shallow water.

(3) Typical deltas in Lake Charles are said to be associated with effluent eskers on the south, marking the course of subglacial or superglacial outlets of the lakelets. The supposed connection of a number of lakelets by these streams accounts for the fact that although no two deltas are at exactly the same level, the discordance of their altitudes is slight. In the Sudbury valley, feeding eskers are common. Effluent eskers are rare. One which runs southward from the southeastern corner of Walden Pond connects the main Walden plain with the plain at Baker's Bridge. The plain one mile due west of South Lincoln station may have been enclosed by ice on all sides; for its southern

border is steep, and several effluent eskers extend out from it. These two cases, only, have been noted in Lake Sudbury as delta deposits which may well have been built in small ice-enclosed lakelets whose outlets on the southern side, through tunnels, perhaps, are marked by eskers. This condition of things, however, is the exception. The sand plains in nearly every case have well developed lobate borders on the southern side, which were clearly built not against an ice-wall, but in open water. Often they have been built forward so far as to nearly overlap the northern end of an older esker. This occurs, for instance, at the western end of the largest South Lincoln plain. Here, as is usual elsewhere, the margin of the plain is not continuous up to the head of the esker; there is a gap of a few hundred feet between the two. Instances have been noted (Woodworth) of cross-sections in sand plains which show where an esker abandoned by the withdrawal of the ice was subsequently buried by the forward extension of a sand delta. In a region where sand plains and eskers are abundant, this overlapping of eskers by deltas is almost inevitable. The mere topographical connection of the two sorts of deposits, therefore, does not prove that they were contemporaneous and that the "effluent" eskers mark outlets rather than inlets; unless as in the Walden plain, the border of the delta, near its junction with the esker, is an ice-contact rather than a lobate border. Aside from the two cases cited, there is nothing to suggest that the eskers in Lake Sudbury are other than feeding eskers. Frequently the eskers broaden out into gravel fans, at intervals, as is shown on the map. Some of these fans may well represent local lakelets in the much decayed ice; but I am inclined to think that as a rule even the fans are true ice-front deposits, built by successive stages at the continually receding mouth of a subglacial tunnel.

(4) "The elevation of all the plains of the system in this part of Lake Charles is very nearly or quite uniform, at about 150 feet above tide." (Clapp, c, 208). Clapp's own figures, however, place the range of discordance of altitudes at no less than 30 feet, — from 140 to 170 feet. This imperfect accordance of altitudes is thought to indicate a state of imperfect connection between the lakelets, by super- or subglacial streams.

Such an explanation whether correct or not, is certainly convenient. It might be successfully applied to any group of discordant sand plains, where the discordance amounts to even more than 30 feet. Recognizing, therefore, that this theory would account for the differences in delta levels in Lake Sudbury, one is tempted to ascribe all discordance there

to a network of lakelets and decaying ice-blocks. The frequent occurrence of deltas with lobes at two or more levels favors this theory; moreover, the extraordinary case of the Saxonville plain has already been explained as due to the wasting of an abandoned ice-block in Lake Cochituate.

On the other hand, the remarkable way in which the many lobe altitudes fall into line, when plotted as in Plate 5, favors the idea that the discordance of levels, on the whole, is not irregular but systematic,— not so satisfactorily explained by isolated lakelets and wasting ice-blocks as by wide open lakes and an ice-front which lay essentially east and west.

Summary.

My conclusions from this study of the sand plains of the Sudbury valley are these: —

(*a*) In late glacial times the basin was occupied by a temporary ice-front lake.

(*b*) This lake underwent successive lowerings of level, in a manner that may be deduced after the horizontal step scheme. At each stage, deltas were built. In some cases, changes of level occurred while the delta was under construction, — notably in the Saxonville sand plain, because that was built forward from a huge ice-block which occupied part of Lake Cochituate long after the main ice-sheet had left it.

(*c*) Perhaps partly during the formation of the deltas — at any rate, after it — the whole region was tilted towards the south. By this tilting apparent confusion of altitudes of the deltas was brought about; but this discordance, when studied with proper accuracy and detail, is seen to be systematic. The tilt seems to be greatest in a due north-south direction, at the rate of about 7 feet per mile.

Further detailed work, in determining the altitudes of the best lobes of a great number of sand plains in the extinct lake basins, ought to demonstrate the truth or incorrectness of the tilting hypothesis. In view of the fact that tilting to some degree is almost certain, from evidence in other parts of glaciated North America and along the New England coast, and that even a short field study of the seemingly discordant deltas in the Sudbury valley goes far towards converting disorder into system, it appears that the grouping of sand plains in eastern Massachusetts may deserve even closer attention than it has usually received.

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PLATE 1.

A. Lobate front of the big Saxonville delta, at its southwestern side. The three high lobes are about 170 feet in altitude, and probably belong to the Morseville water-plane. Just to the right of the house, and below it, is a lower lobe which belongs to one of the lower water-planes.

B. Water-worn surface of a ledge near Hobbs' Brook reservoir, mentioned on page 294. This may possibly record the work of a torrential outlet of Lake Sudbury.

A. LOBES SOUTH OF SAXONVILLE.

B. WATERWORN LEDGE NEAR HOBBS BROOK.

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PLATE 2.

A. Double lobe-border of the big Saxonville delta at its northwestern corner (see pages 289 and 295). In the foreground is one of the low (137-foot) lobes, sloping down to the flood-plain of the Sudbury River, on the right, where horses are grazing. Beyond, in the centre of the picture, the doubly lobate front is seen in profile, — the higher 161-foot lobe sloping smoothly down to a 137-foot lobe.

B. Another view of the northwestern border of the Saxonville delta. The same 161-foot lobe is seen nearer than before; and part of the frontal slope of another lobe of the same group (165 feet) in the immediate foreground. On the right is the 137-foot terrace. Exactly in the centre on the picture, the intermediate (149-foot) lobe is very indistinctly shown in profile, occupying an interlobate hollow between the two higher lobes.

A. DOUBLE LOBE-BORDER NEAR SAXONVILLE.

B. LOBES NORTH OF SAXONVILLE.

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PLATE 3.

Tilted water-planes of Lake Sudbury. The significance of this diagram may best be seen by superposing it on Plate **4**, to which it is supplementary. It shows how the same points, plotted as in Plate **4**, might less perfectly be grouped into a series of more steeply tilted planes, which slant about 13 feet to the mile. (See page 295.)

PLATE 4.

Tilted water-planes of Lake Sudbury. The altitudes of lobes and outlets, given on the map (Plate **5**), are plotted in profile, with reference to a north-south line. The points fall close to a series of planes which rise northward at the rate of about 7 feet to the mile. The horizontal scale is the same as in Plate **5**; vertical exaggeration about 75.

Base line = sea level
S
MORSEVILLE WATER - PLANE
CONFLUENT WATER-PLANE
WESTON WATER-PLANE

PLATE 5.

Map of Glacial Lake Sudbury, showing the probable boundary of the lake and the distribution of sand plains and eskers within its limits. The altitudes of lobes and of passes in the rim of the basin are given in feet (above mean low water. — Boston City base). The separation into groups, marking several successive water-planes, seems justifiable in view of the data presented in this paper, and summed up in Plate 4.